
**Characterising the Outbursting Mechanisms of
Centaur 29P/Schwassmann-Wachmann 1 by
Engaging Schools in the Research Process**

Ioan Cai Stoddard-Jones

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“Er gwaethaf pawb a phopeth, ry’n ni yma o hyd.”

- Dafydd Iwan

Abstract

The underlying mechanisms responsible for the frequent and violent outbursts of 29P/Schwassmann–Wachmann 1 (29P/SW1) are still poorly understood. This thesis characterises the photometric behaviour of 29P/SW1 during these outbursts using data obtained in part by school students in Wales as part of the Comet Chasers STEM educational outreach programme.

Images collected through a global robotic telescope network, Las Cumbres Observatory, between May 2016 and July 2025 were processed using a Python pipeline to consistently measure the magnitude of 29P/SW1. An average of 15.3 ± 1.0 outbursts per year with $\Delta m > 0.2$ mag were identified and classified as major, moderate, or minor. The number of outbursts in each category varies significantly between apparitions. Overall, 29P was found to be brighter than its quiescent level for more than 80% of the time.

The mean colour indices were $g' - r' = 0.49$ mag and $r' - i' = 0.29$ mag. These indices vary slightly during the surge phase of an outburst, with changes of $\Delta(g' - r') = -0.25 \pm 0.30$ mag and $\Delta(r' - i') = -0.01 \pm 0.08$ mag. A mean photometric decay rate of 0.10 ± 0.10 mag d⁻¹ was measured, with higher-intensity outbursts exhibiting faster decay. Ejecta expansion velocities were estimated as $v_{dust} < 0.1$ km s⁻¹ and $v_{gas} \sim 0.4$ km s⁻¹.

Students participating in Comet Chasers reported high levels of engagement with the practical, student-led research activities. Introducing young learners to active scientific research shows strong potential for encouraging interest in STEM subjects: space was identified as a particularly popular topic among 8 to 11-year-olds, with over 20% expressing interest in pursuing a STEM-related career in the future.

These findings contribute to a deeper understanding of 29P/SW1's unusually active behaviour while demonstrating the scientific value and educational benefits of involving school students directly in contemporary astronomical research.

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“If you are sure you understand everything that is going on, you are hopelessly confused.”

Walter F. Mondale

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Glossary

aphelion Furthest distance from the Sun. [xiv](#), [xxiii](#), [59](#), [82](#), [114](#), [250–252](#), [257](#)

bilobate Consisting of two lobes. [52](#), [104](#)

cryomagma Liquid hydrocarbons containing dissolved gasses. [3](#), [102](#), [120](#), [322](#)

eccentricity Measure of how circular an orbit is. 0 represents a perfect circle.
[xi](#), [53](#), [58–60](#), [77](#), [80](#), [82](#), [248–250](#)

frost line Distance from a star at which solid volatile compounds begin to sublimate [3](#), [60](#), [70](#), [71](#), [80–82](#), [95](#), [98](#), [106](#)

geocentric Relating to the Earth. [x](#), [63](#), [64](#), [90](#), [112](#), [242](#), [276](#), [277](#), [286](#), [287](#)

heliocentric Relating to the Sun. [x](#), [xi](#), [xiv](#), [3](#), [42](#), [51](#), [60](#), [63](#), [64](#), [70–72](#), [75–77](#),
[83](#), [88](#), [95](#), [96](#), [98](#), [101](#), [106](#), [112](#), [120](#), [242](#), [249–252](#), [257](#), [276](#), [277](#), [286](#), [287](#),
[338](#)

perihelion Closest distance from the Sun. [xiv](#), [xxiii](#), [3](#), [41](#), [43](#), [48](#), [52](#), [59](#), [60](#),
[69](#), [71](#), [73](#), [77–79](#), [82](#), [114](#), [248](#), [250–252](#), [257](#), [258](#)

quiescence Period in which an object exhibits little to no detectable activity.
[84](#), [106](#), [112](#), [287](#), [288](#), [313](#)

refractory Materials which have a high condensation temperature, usually metals or rocks in astronomy. [49](#), [74](#), [75](#), [77](#)

sub-solar point Position directly underneath the Sun. [96](#), [102](#), [106](#), [252](#), [322](#)

sublimation Phase transition from solid directly to gas. [xi](#), [xviii](#), [3](#), [48](#), [70–72](#),
[75](#), [77](#), [79](#), [95](#), [96](#), [98–100](#), [104](#), [106](#), [107](#), [111](#), [252](#), [258](#), [322](#)

volatile Molecules which can be vaporized at lower temperatures (e.g. water, carbon monoxide, carbon dioxide, ammonia, etc.) [49](#), [51](#), [52](#), [54](#), [69](#), [70](#),
[75](#), [79](#), [80](#), [95](#), [103](#), [104](#), [106](#), [252](#), [322](#), [324](#)

Acronyms

29P/SW1 29P/Schwassmann-Wachmann 1 [xi](#), [xiv–xvi](#), [xviii](#), [xxii](#), [xxiii](#), [3–5](#),
[59](#), [60](#), [68–70](#), [72](#), [74](#), [79](#), [81–85](#), [87](#), [89–96](#), [98–106](#), [112–116](#), [119](#), [120](#), [240](#),
[248–252](#), [254–258](#), [260](#), [263–268](#), [271](#), [276–278](#), [280](#), [285](#), [287](#), [303](#), [304](#), [307](#),
[308](#), [313](#), [314](#), [317](#), [318](#), [321](#), [322](#), [324](#), [326](#), [327](#), [334](#), [335](#), [337](#), [338](#)

67P/CG 67P/Churyumov–Gerasimenko [x](#), [xi](#), [45](#), [49](#), [50](#), [70](#), [72](#)

ATel Astronomer’s Telegram [30](#), [115](#), [252](#)

AWI Amorphous Water Ice [xi](#), [xviii](#), [3](#), [52](#), [71](#), [79](#), [95–101](#), [103](#), [104](#), [110](#), [120](#),
[322](#), [325](#)

BAA British Astronomical Association [xiv](#), [115](#), [255](#), [260](#)

CCD Charged-Coupled Device [43](#), [64–66](#), [315](#), [316](#)

CfW Curriculum for Wales [1](#), [14](#)

CTC Chiron-Type Comet [56](#)

CWI Crystalline Water Ice [xi](#), [xviii](#), [3](#), [52](#), [71](#), [79](#), [95–101](#), [104](#), [106](#), [110](#), [120](#),
[322](#), [325](#)

DS1 Deep Space 1 [44](#)

EKB Edgeworth-Kuiper Belt [x](#), [49–51](#), [58](#), [59](#), [71](#), [74](#), [77](#), [78](#)

ETC Encke-Type Comet [56](#)

- FSM** free school meals [8](#), [9](#)
- FTN** Faulkes Telescope North [68](#), [116](#), [117](#)
- FTS** Faulkes Telescope South [68](#), [116](#), [117](#)
- HTC** Halley-Type Comet [56](#), [58](#), [78](#)
- IAOS** International Astronomical Observatory Sanglokh [92](#)
- ICE** International Cometary Explorer [43](#), [44](#)
- IR** Infrared [ix](#), [xiii](#), [xxi](#), [26–28](#), [34](#), [68](#), [88](#), [93](#), [128](#), [130](#), [143–145](#), [200–207](#), [217–220](#), [222](#), [231–234](#), [236](#), [237](#), [328–330](#), [337](#)
- JFC** Jupiter Family Comet [x](#), [52](#), [56](#), [58–60](#), [74](#), [75](#), [78](#), [79](#), [81](#), [82](#), [84](#), [89](#), [94](#), [99](#), [120](#)
- JPL** Jet Propulsion Laboratory [x](#), [54](#), [56](#), [57](#), [242](#), [248](#), [249](#)
- JWST** James Webb Space Telescope [x](#), [xi](#), [67](#), [104](#), [105](#)
- KBO** Kuiper Belt Object [51](#), [52](#), [59](#), [73](#), [77](#), [79](#)
- LCO** Las Cumbres Observatories [ix](#), [xxiii](#), [25](#), [29](#), [31](#), [67](#), [92](#), [115](#), [116](#), [118](#), [128](#), [225](#), [241](#), [242](#), [247](#), [260–262](#), [269](#), [289](#), [308](#), [309](#), [314](#), [315](#), [318](#), [325](#)
- LPC** Long Period Comet [51–53](#), [56](#), [58](#), [69](#), [78](#), [83](#)
- MOE** Multi-Outburst Events [xv](#), [114](#), [280](#), [283](#), [285](#), [286](#), [290](#), [296](#), [297](#)
- MPC** Minor Planet Center [xiv](#), [249](#), [252](#), [255](#)
- MuSCAT** Multicolour Simultaneous Camera for studying Atmospheres of Transiting exoplanets [iii](#), [xi](#), [116–118](#), [308](#)
- NASA IRTF** NASA Infrared Telescope Facility [92](#)
- NEO** Near Earth Object [57](#)

- NPS** Net Promoter Score [35](#), [36](#), [179](#), [184](#), [200](#), [201](#), [209](#), [215](#), [216](#), [229](#), [231–233](#)
- PDM** Phase Dispersion Minimisation [85](#), [87](#)
- PISA** Programme for International Student Assessment [1](#), [6](#), [7](#), [9](#), [10](#), [12](#)
- PNTA** Prefer not to answer [xx–xxii](#), [146](#), [148](#), [149](#), [153](#), [156](#), [158](#), [181](#), [183](#), [186](#),
[189](#), [193](#), [195](#), [196](#), [198](#), [203](#), [205](#), [207](#), [208](#), [210](#), [212](#), [214](#), [217](#), [219](#), [221](#),
[226](#), [228](#), [230](#)
- PSF** Point Spread Function [xiv](#), [242–244](#)
- SAO** Smithsonian Astrophysical Observatory [249](#)
- SEP** Source Extraction and Photometry Python Package [241](#), [243](#), [244](#)
- SNR** Signal-to-Noise Ratio [xiv](#), [xv](#), [245](#), [247](#), [269–276](#), [318](#)
- SOE** Single-Outburst Events [280](#), [283](#)
- SPC** Short Period Comet [51–53](#), [56](#), [58](#), [59](#), [69](#), [84](#), [99](#), [100](#)
- SS** Solar System [x](#), [xi](#), [38](#), [43](#), [48](#), [50–53](#), [55](#), [58–61](#), [71](#), [73](#), [74](#), [77](#), [82](#), [83](#), [95](#),
[101](#), [120](#), [338](#)
- STEM** Science, Technology, Engineering, and Mathematics [xii](#), [xix](#), [1](#), [2](#), [5](#), [6](#),
[12](#), [15](#), [16](#), [18–25](#), [33](#), [34](#), [123](#), [125](#), [135](#), [146](#), [147](#), [149–151](#), [153–158](#), [161](#),
[162](#), [164](#), [179](#), [180](#), [235](#), [327](#), [328](#), [330](#), [331](#), [333](#), [334](#), [337](#)
- TNO** Trans-Neptunian Object [xi](#), [57](#), [59](#), [61](#), [72–78](#), [82](#), [88](#), [120](#)
- UH** University of Hawaii [92](#)
- WIMD** Welsh Index of Multiple Deprivation [140](#)
- WISE** Wide-field Infrared Survey Explorer [92](#)

Physical Constants

Astronomical Unit	AU	$=$	$1.496 \times 10^{11} \text{ m}$
Stefan—Boltzmann Constant	σ_{SB}	$=$	$5.670 \times 10^{-8} \text{ W m}^{-2} \text{ K}^{-4}$
Solar Luminosity	$L_{\odot}$	$=$	$3.828 \times 10^8 \text{ W}$
Gravitational Constant	G	$=$	$6.67 \times 10^{-11} \text{ m}^3 \text{ kg}^{-1} \text{ s}^{-2}$

Symbols

Δ	Geocentric distance	AU
r_H	Heliocentric distance	AU
r_J	Distance to Jupiter	AU
m	Apparent magnitude	mag

T	Orbital period	yr
a	Semi-major axis	AU
q	Perihelion distance	AU
Q	Aphelion distance	AU
e	Eccentricity	
i	Orbital inclination	°

Chapter 1

Overview and Purpose of Study

If students do not express an interest in science by age 14, they are not likely to want to continue learning about science post-16, with even fewer aiming for a job in a [Science, Technology, Engineering, and Mathematics \(STEM\)](#) field (Archer Ker et al. [2013](#)). Nurturing interest in science at a young age is key to encouraging participation and desire of students to opt for a career in [STEM](#) in their adult lives. Students' positive attitudes towards science decreases as they age (Pell and Jarvis [2001](#)), this is a trend amplified in under-represented groups in [STEM](#) (Barmby et al. [2008](#)). Only those from backgrounds with high science capital are likely to continue enjoying and pursuing [STEM](#) subjects in school and beyond (Appel et al. [2021](#)).

Students respond positively to [STEM](#) workshops and hands-on experiments, potentially causing longer-term impact compared with conventional school lessons (Mateos-Núñez et al. [2020](#); Timur et al. [2020](#)). Activities are effective to interest students in under-represented groups with all students preferring this type of learning over lessons (Appel et al. [2021](#); Vennix et al. [2018](#)).

Due to multiple compounding challenges, education in Wales has not been serving its purpose, with poor [Programme for International Student Assessment \(PISA\)](#) test scores highlighting the discrepancy between students in Wales, other countries in the UK, and abroad. With the introduction of the [Curriculum for](#)

Wales (CfW) (Welsh Government 2023), policy makers hope that giving teachers and schools more freedom to explore topics, focussing on teaching skills rather than content, will yield better-performing and students are more prepared students for their future. This shift in teaching practices is not without its pitfalls, leading to educators feeling ill-prepared and lacking resources to deliver new lessons (Thomas et al. 2023).

Outreach interventions were conducted in multiple schools in Wales, delivering hands-on activities. Pre-engagement surveys were distributed to assess students' science capital and interest in science, primarily in students residing in rural areas in North Wales. Post-engagement surveys were distributed to assess students' enjoyment and understanding of the activities conducted during the workshop. Their responses were used to gain an impression of students in Wales's impression of science, astronomy, and experimental activities. The aim of Comet Chasers is to provide schools with a ready-to-go education programme, which uses astronomy as a vehicle to teach essential skills, this study investigates if this is a valuable and worthwhile endeavour.

How can real scientists help students, to nurture their enjoyment of STEM subjects, and educators, by sharing their knowledge and current research?

Comet Chasers is an astronomy-based educational programme aimed at involving schools in new and current comet and asteroid research. Multiple hands-on experiments have been developed by the programme to teach students about astronomical concepts, using fun and creativity as a vehicle to teach. This study builds on theses by Bartlett (2018) and Usher (to be submitted), investigating the influence of students' engagement with science via astronomy, but focuses on how the data obtained by schools can be used, and how much of an invaluable tool this can be to obtain regular and high quality astronomical images. While previous studies have explored engagement and activity outcomes, there remains limited investigation into how pupil-generated astronomical images contribute to professional research. Additionally, schools have been contributing to research for over 10 years, by using robotic telescopes across the world to image objects

of interest in space. Numerous publications have acknowledged schools' contributions via the Comet Chasers programme (Cordiner et al. 2025; Ferellec et al. 2024; Kelley et al. 2023b), while also providing a significant number of regular observations of 29P/Schwassmann-Wachmann 1 (29P/SW1).

29P/SW1 is a very unusual object, with intense and frequent outbursts, an almost circular orbit, large heliocentric distance, and large nuclear size. Despite being intensely imaged by professional and amateur astronomers for the last quarter of a century, there is still great uncertainty regarding the nature of this object and the mechanism(s) driving these iconic outbursts. Its orbit remains firmly outside of the frost line, therefore activity seen cannot be driven by water-ice sublimation, as is seen in 'regular' comets at they approach perihelion. Two main schools of thought exist regarding the driving of these outbursts: first, that they are triggered by crystallisation of AWI into CWI (Lisse et al. 2022; Trigo-Rodríguez et al. 2008b), and triggered by cryovolcanism due to cryomagma in cavities beneath the crust (Gronkowski 2014; Miles 2016a). A photometric pipeline was written to process the images available for a consistent and complete analysis of the dataset.

Studies of 29P/SW1 have focused on single outbursts or, at most, spanning a few apparitions. The dataset supplemented by Comet Chasers' schools allows a longer-term, in-depth analysis of the objects, with opportunities to observe general trends during outbursts and photometric changes occurring over years. Without a dedicated programme aiding professional astronomer observations of the Centaur, such a high-quality, long-term dataset would not be possible. This study aims to begin to characterise the outbursts, how they vary between apparitions and, ultimately, propose the mechanism(s) responsible for such activity. This research should be used as a starting point for further longer-term analysis of this odd object, and short-term research to compare outbursts.

1.1 Research Objectives

Due to the nature of this thesis, the primary research objectives are separated into two groups, focussing on the pedagogy and cometary science aspects.

Pedagogy

This section focuses on the Comet Chasers educational outreach programme and questionnaire responses obtained following workshops.

- 1 To systematically investigate the impact of sustained student participation in authentic astronomical research on engagement, motivation, and disciplinary identity, using a mixed-methods longitudinal design.
- 2 To critically evaluate the extent to which student-generated contributions can be integrated into professional astronomical research workflows without compromising scientific rigour, and to identify conditions under which such integration adds novel research value.

Cometary Science

This section investigates the behaviours and potential mechanisms of centaur [29P/SW1](#).

- 3 To characterise the outburst behaviour of the target object(s) through long-baseline time-domain photometry, quantifying recurrence timescales, duty cycles, and outburst morphologies.
- 4 To perform a detailed quantitative analysis of photometric evolution during outburst events, including multi-band magnitude, colour, and temporal variability, and to identify statistically significant patterns across events.
- 5 To constrain the physical mechanisms driving the observed outbursts by comparing empirical results with existing theoretical models and, where appropriate, proposing refinements or alternative interpretations.

1.2 Chapters' Summaries

A summary of the contents of each chapter has been included for convenience.

- **Chapter 2:** Literature review of pedagogical research, primarily focussing on [STEM](#) education and challenges facing education in Wales.
- **Chapter 3:** Foundations of cometary science, Centaurs, and [29P/SW1](#).
- **Chapter 4:** Comet Chasers' trial outreach interventions including feedback received.
- **Chapter 5:** Analysis of pre- and post-engagement evaluation received following numerous workshops conducted in schools in Wales.
- **Chapter 6:** Development and features of Python photometric pipeline written to analyse large astronomical image datasets.
- **Chapter 7:** Collated data over almost a century of [29P/SW1](#) with analysis of orbital changes.
- **Chapter 8:** Analysis of this [29P/SW1](#) dataset, investigating quiescent data, outburst frequencies, surge and decay rates, colour variation, dust production, and a detailed look into an outburst.
- **Chapter 9 and 10:** Discussion and conclusion of findings of this study.

Chapter 2

Pedagogy Introduction

2.1 Education in Wales

For many years, Wales has consistently underperformed in education compared to its international peers. Clear changes are required to ensure Welsh students receive the highest quality of education possible.

OECD's [PISA](#), assesses 15-year-olds' abilities across several academic subjects. [PISA](#) tests ascertain students' abilities in reading, Mathematics, and Science from numerous countries, with the aim of comparing different countries' ranking with respect to education (OECD 2025). Wales' [PISA](#) test scores have been tracked since 2009, and have shown significant declines in subsequent [PISA](#) tests.

As expected, [PISA](#) test scores declined globally following the COVID-19 pandemic, but Welsh results declined significantly compared to most other countries. After assessing these discrepancies with other countries, most notably England, Sibieta (2024) find major discrepancies in results [STEM](#) from differences in policies and approaches towards education between Y Senedd in Wales and the UK Government (who dictate England's education policies).

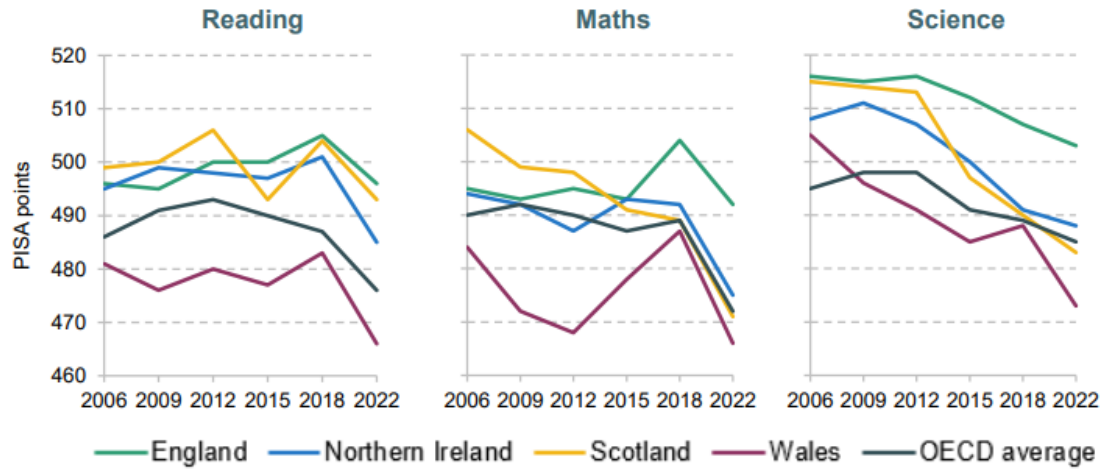


FIGURE 2.1: PISA test results for reading, maths, and science for each nation within the UK over time. Credit: Sibieta (2024).

Rees and Taylor (2015) notes that while education in Wales is trailing other countries in the UK, it is not as extreme as PISA results portray, due to the tests sampling a larger proportion of schools in Wales ($\sim 17\%$) than those in England ($< 1\%$ (Gov.uk 2023)). Additionally, Welsh students do not sit exams at the end of their time at primary school, unlike their counterparts in England, hence inexperience in test-taking could lower scores. (Davies 2016).

In Wales, disadvantaged students trail their peers by an approximate equivalent of 23 months of education (Cardim-Dias and Sibieta 2022), this is higher than compared with the inequality gap in England (18 months). Additionally, schools in both rural areas and cities in Wales have a smaller disadvantage gap (17-20 months) than the UK average, although this only puts these areas on par with the average gap in England (Cardim-Dias and Sibieta 2022).

Numerous factors contribute towards a unique and challenging environment for education to thrive, such as large proportions of child poverty, bilingual education, and numerous rural communities. These factors are further investigated below.

2.1.1 Child Poverty

Between 2020 and 2022, 28% of children in Wales live in relative income poverty, according to research by Y Senedd (Murphy 2023). Until recently, of the four countries in the United Kingdom, Wales has historically had the largest proportion of children living in poverty, see fig. 2.2.

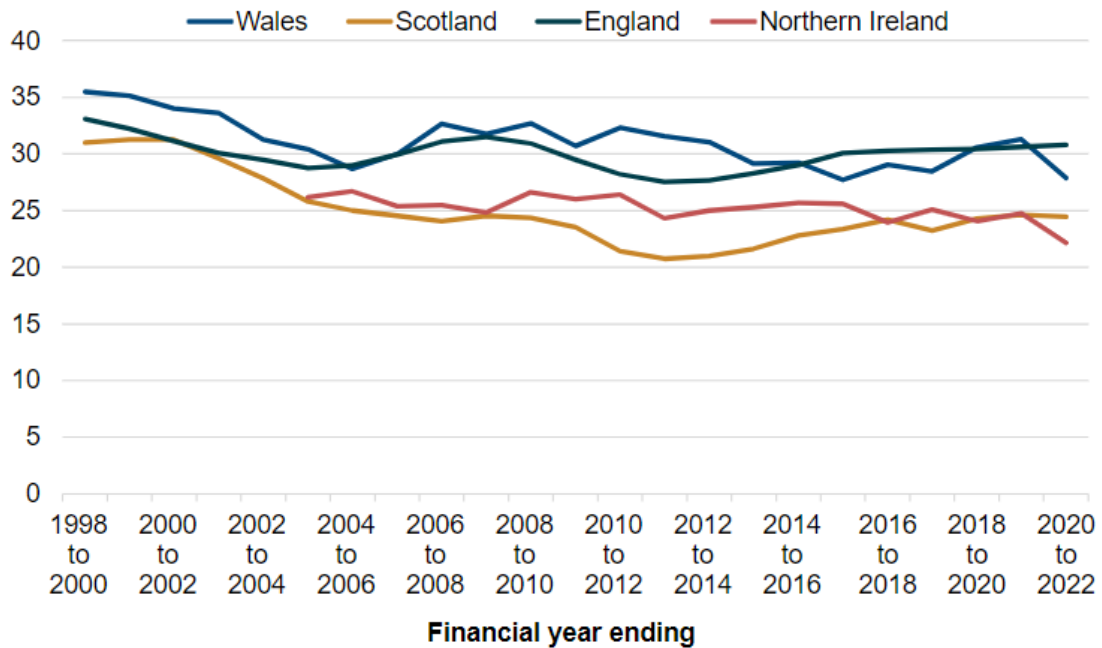


FIGURE 2.2: Percentage of children living in financial poverty over time for the four nations within the United Kingdom. Credit: Murphy (2023)

In the past, this high rate of child poverty naturally results in a larger number of students eligible for [free school meals \(FSM\)](#). This value can be used to assess the deprivation of a school.

Data obtained from the Welsh Government (2025b) for Wales and the Department for Education (2010, 2017, 2022) for England have been used to recreate a plot from Cardim-Dias and Sibieta (2022), see fig. 2.3. Unfortunately, students eligible for [FSM](#) are far less likely to achieve 5+ GCSEs with grades A* to C than students not eligible for [FSM](#). While the proportion of all students achieving this criterion is increasing over time, the gap between [FSM](#) and non-[FSM](#) students remains fairly constant, see fig. 2.3. This indicates that while the standard of education is increasing due to an increase in the proportion of students

achieving this criterion, currently, there are insufficient interventions to assist disadvantaged students, thereby failing to close the disparity. These trends are consistent for both Wales and England.

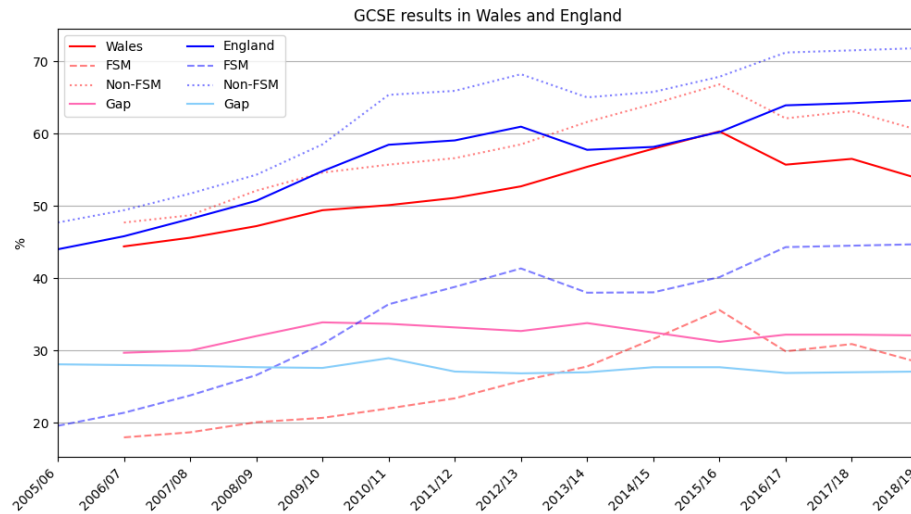


FIGURE 2.3: GCSE results in Wales and England over time. For Wales, the percentage value represents the proportion of students obtaining 5 GCSEs with grades A*–C. For England, pre-2015/16 data uses the same criteria as Wales, post-2015/16 data uses the proportion of students achieving A*–C grade in GCSE English and Mathematics. Data credit: Welsh Government (2025b) for Wales, Department for Education (2010, 2017, 2022) for England.

For context, any England data prior to the 2016/17 academic year uses the same criteria as Wales, i.e. students achieving 5 GCSEs with grades A*–C. After the 2010/11 school year, the data obtained has the criteria of students achieving at least a C (or level 4 since the grade changes) in English and Mathematics. For those years with data for both criteria, an average is calculated for simplicity.

Students in Wales underperform compared to their peers in England. This is seen in fig. 2.3 for overall GCSE results, and when compared with PISA test results for reading, maths, and science, see fig. 2.1.

There is a strong correlation with the proportion of students eligible for FSMs and a lower pupil-to-teacher ratio, especially for primary schools, fig. 2.4. Si-bieta (2020) notes that more deprived schools use their additional budget to hire more staff, or that these schools are in more rural areas and would naturally have fewer students attending.

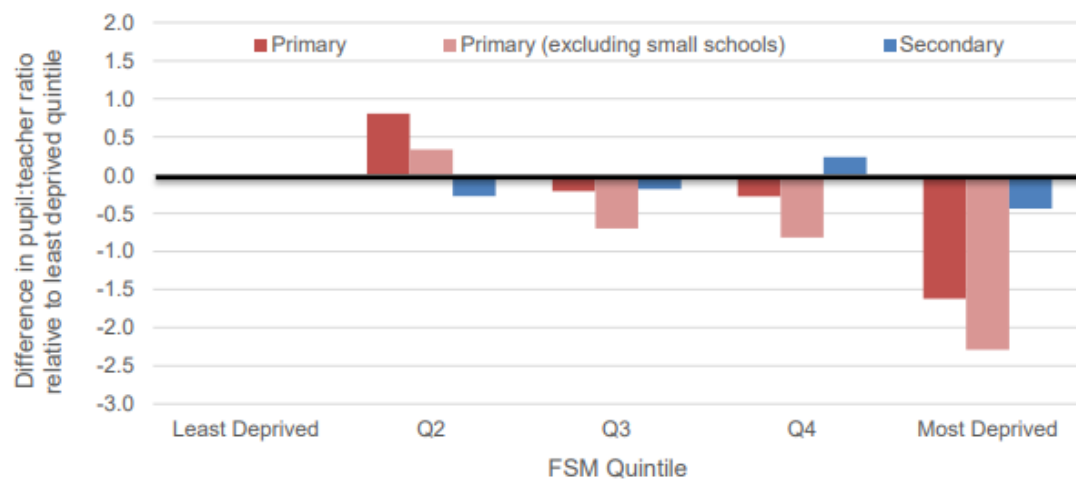


FIGURE 2.4: Pupil-to-teacher ratio of schools in Wales with respect to the proportion of students eligible for FSMs. Credit: Sibietā (2020).

While children living in financial poverty may not be the root cause of the educational problems in Wales, it is an issue to education within Wales and further afield - Sibietā (2024) discusses that disadvantaged students in England perform better than disadvantaged Welsh students in [PISA](#) tests. Schools in areas of significant financial poverty have a lower percentage of students achieving 5 GCSEs graded A*–C (Sibietā 2024). Sibietā (2020) notes that there has been a 6% reduction in real-term funding per student in Wales between 2008 and 2019, similar to the real-terms reduction in the block grant provided by the UK Government. To reduce the gap between disadvantaged and non-disadvantaged students, targeted interventions are essential, see fig. 2.3.

2.1.2 Welsh Language

Until the mid-1900s, Welsh was rarely used in schools in Wales, following reports (Johnson et al. 1848) and the adoption of punishments for speaking Welsh. Numerous revitalisation measures have resulted in many more Welsh or bilingual schools throughout the country along with the introduction of ‘Cymraeg pob dydd’ (‘Welsh everyday’) in the new curriculum (Parry 2021).

Welsh-medium schools naturally have additional challenges compared with English-medium schools, due to having to teach bilingually. Primarily, these focus on how Welsh-medium and bilingual schools support those who come from Welsh-speaking, and non-Welsh-speaking homes (Lewis 2008). Students in Welsh-medium schools appreciate the importance of using Welsh in their future workplace, although they also see the importance of studying certain subjects in English to assist those who may, in the future, work or study outside Wales (Thomas et al. 2024). The primary reason a student would not choose to study a subject in Welsh is their self-perception of their Welsh language ability (Thomas et al. 2024). Ensuring that Welsh learners are able to learn and contribute effectively in schools is crucial for their development, balanced together with providing first language Welsh students with the resources and encouragement in their native tongue (Lewis 2008).

Thomas et al. (2024) identifies that switching between Welsh and English in classrooms is an aid to all students. This can help those less confident in Welsh to fully understand what is being taught, while for those who are confident in Welsh, it reinforces what they are learning, additionally raising awareness of English definitions. Using a language other than English in the class could aid learning, especially with terminology which is more intuitive in Welsh (Thomas et al. 2024). For example, ‘volcano’ in Welsh is ‘llosgfynydd’, translated literally it means ‘burn mountain’, far more understandable than referencing a Roman god.

Conducting education in a minority-language can function well in the school environment, but students will encounter the majority-language far more often outside the classroom, especially for students from non-minority-language speaking backgrounds. Teaching a student a language is not useful if they have no reason or possibility to use it outside of school time (Ó Duibhir 2019). This is not an issue exclusive to the Welsh language, with Irish, Gaelic, Basque, and Valencian all having required revitalisation, with a need to balance their use with

the majority language. Reducing the gap between those who can speak the language and those who use it daily is essential for the resurgence of the language. (Ó Duibhir 2019).

Students recognise that STEM education has an English language bias, however students at Welsh-medium schools will primarily opt for studying the subjects in Welsh if given an option (Thomas et al. 2024). Additionally, Thomas et al. (2024) notes that whether the student speaks Welsh at home or not, does not influence the student's decision to continue their lessons in Welsh/bilingually.

Despite the poor PISA results in Welsh medium schools, there is evidence to suggest that this may be an issue with the test's translation into Welsh. Jerrim (2023) suggests that due to the small proportion of Welsh students in the UK (let alone Welsh language students), the PISA tests are only nationally, not internationally, verified. This may have resulted in changes to the test that make it unfairly more difficult than tests in other languages. The 'Technical Report' for the 2012 PISA tests mentions that only tests in Irish, Valencian, and Welsh were not internationally verified (OECD 2014). An investigation into test results conducted in Welsh, Irish and Valencian may help confirm if this is a cause of the discrepancies between tests conducted in Welsh and English. Furthermore, Jerrim (2023) references Fife (1986) discussing the differences between spoken and written Welsh. This could have affected the understanding of the questions, especially if the dialect the questions are written in is not familiar to the student (broadly, North and South Welsh dialects).

Exam results for students conducting exams either in the medium of Welsh or English are not broken down in *StatsWales*. Examining the differences in the proportion of students achieving grades A* - C according to the language of the exam would provide valuable insight into whether exam language influences student performance.

2.1.3 Education in Rural Communities

Roughly a third of the population of Wales live in a rural area, broadly defined as an area with a population fewer than 10,000 (Office for National Statistics 2026). This is a larger percentage of the population compared with England and Scotland (18% and 29%, respectively) (NRS 2022; Office for National Statistics 2011a). Table 2.1 summarises these proportions. 21% of the population of Wales reside in one of the three biggest cities: Cardiff, Swansea, and Newport (Office for National Statistics 2023).

TABLE 2.1: Proportions of people who live in urban and rural areas in each country within the UK. Urban areas are defined as places with a population of > 10,000, as defined by the Office of National Statistics.

Country	Total Population	Urban Population (%)	Rural Population (%)
England ¹	53,012,456	82.4	17.6
Scotland ²	5,299,900	71.5	28.5
Wales ³	3,063,456	67.2	32.8
N. Ireland ⁴	1,810,863	56.0	44.0

¹ Office for National Statistics (2011a)

² NRS (2022)

³ Office for National Statistics (2011b)

⁴ NISRA (2017)

In rural areas, teachers are less likely to have access to collaboration or support services compared with their urban counterparts (Handal et al. 2013), leading to reduced uptake of teaching jobs in rural areas (Hutchinson et al. 2024). The COVID-19 pandemic naturally interrupted the status quo of schools, with an increased technology use in teaching during this period (Mustafa et al. 2024). Murphy (2025) investigated collaboration between schools, finding that it initially increased during the pandemic yet returned to pre-pandemic levels shortly afterwards.

Moreover, rural areas are more likely to have higher levels of socio-economic deprivation, adding additional challenges which includes lower aspirations after leaving school (Johnson and Strange 2007).

2.1.4 Curriculum for Wales

Following a review by Donaldson (2015), it was apparent that the curriculum in Wales required reform to better equip students for their futures and to ensure that Wales did not further fall behind other countries, especially regarding scientific literacy.

A new curriculum was introduced in Wales in 2022, aptly named [Curriculum for Wales \(CfW\)](#), which shifts the focus from content-based to skills-based learning (Welsh Government 2023). These well-intentioned efforts have the potential to revolutionise education in Wales, it, nonetheless, puts teachers in a difficult situation as it is now wholly up to them, and their school to create lessons, currently with very little guidance. Evans (2023) proposes that additional support for teachers, as the curriculum was introduced, could have boosted their confidence and allowed early testing of different teaching methods.

Primary school children have enjoyed learning via projects which lets them explore topics in more depth, allowing opportunities for them to be involved in decisions regarding their learning thus leading to additional motivation and a sense of ownership (Thomas et al. 2023).

Funding issues cause additional problems for schools as it is impossible to dedicate the resources and time teachers need to create and develop new and exciting lessons (Thomas et al. 2023).

This thesis investigates the effectiveness of Comet Chasers, an astronomical educational school programme based in Wales to teach students about space to ignite their interest in the topic. Further details are presented in sect. 2.4. Comet Chasers can give schools access to high-quality resources along with ‘loan boxes’ to conduct their own experiments and investigations - this is covered further in sect. 2.4. Due to budget restraints, resources such as the Rotato experiment and meteorite loan boxes would not be accessible to schools if they were required to buy or rent the equipment.

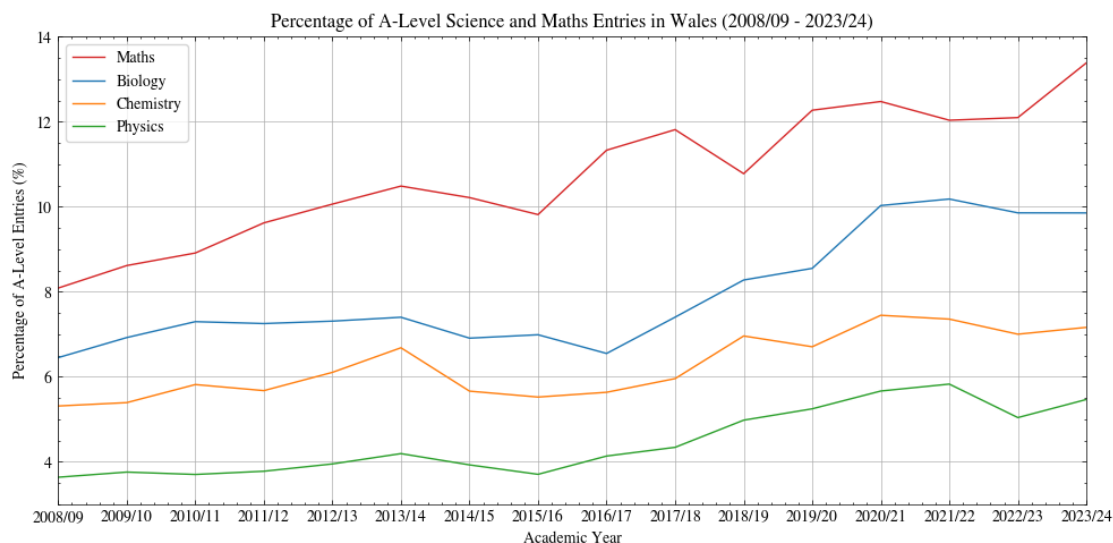


FIGURE 2.5: Percentage changes of A-level entries for Maths, Biology, Chemistry, and Physics in Wales over time. Data spans from 2008/09 to 2023/24 academic years. Data credit: Welsh Government (2025b).

2.1.5 STEM in Welsh Schools

Uptake of core STEM subjects (Maths, Biology, Chemistry, and Physics) as a proportion of total A-level entries have increased since the 2008/09 academic year, see fig. 2.5. Maths is the most popular STEM subject with Physics being the least popular of the core subjects. Since the 2016/17 academic year, a more definite increase in the core STEM subjects has occurred.

Students who speak Welsh at home are less likely to study a STEM subject at A-level than those who are from non-Welsh-speaking backgrounds (Thomas et al. 2024), which could be due to a lack of Welsh language STEM events offered (Hatch et al. 2024).

Since 2012/13, of all the core STEM subjects in Wales, Biology has consistently more female entries at A-level than male entries. Other STEM subjects are male-dominated, with only Chemistry significantly narrowing the gender gap in recent years. Chemistry sees a large surge in male entries in 2013/14 year, but in the following year it is significantly reduced¹. Figure 2.6 shows the proportional change over time for each of the core STEM subjects.

¹This is a highly anomalous point, and strangely corresponds with the release of the final season of ‘Breaking Bad’.

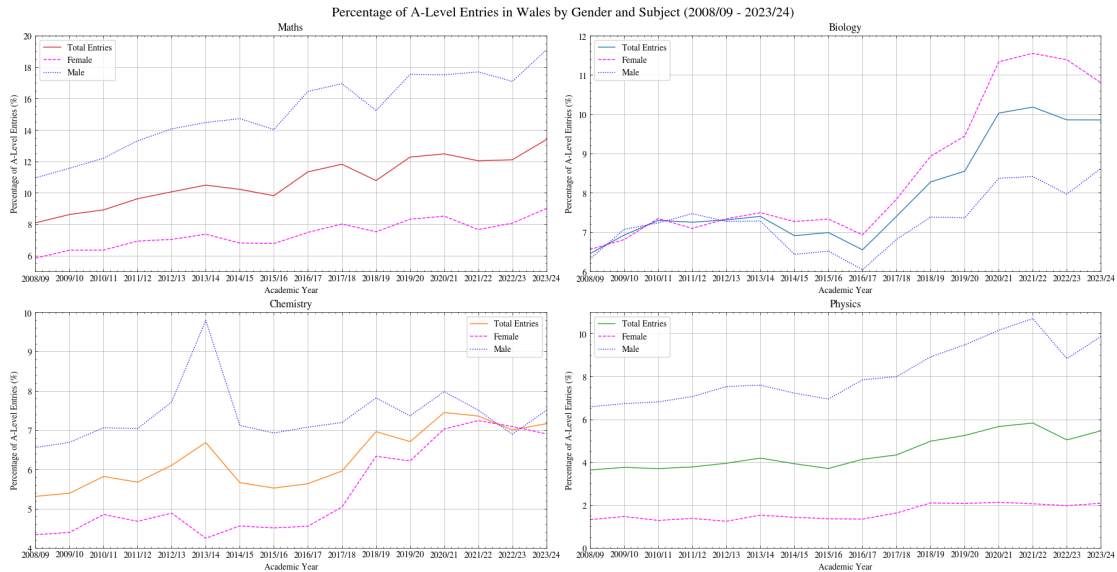


FIGURE 2.6: Percentage of male and female A-level entries for Maths, Biology, Chemistry, and Physics in Wales over time. Data credit: Welsh Government (2025b).

We investigate the proportion of female students in the core STEM subjects in fig. 2.7. Between 2008/09 and 2013/14, Biology’s proportion of female students in classes is very similar to the proportion of female students in the year. Following 2013/14, the proportion of female students in Biology increases, deviating from the general proportion of students. The proportion of young women taking Chemistry increases, and reached similar proportions as the general A-level population since 2021/22. In Physics, the proportion of young women has remained fairly consistent since the 2008/09 academic year, with around a fifth of the class consisting of female students. We see a slight decrease in the proportion of female students in Maths over time,

Compared with other countries in the UK, Wales has a higher proportion of entries at A-level for most core STEM subjects, see table 2.2. Entries of Chemistry in England are only marginally greater compared with Wales.

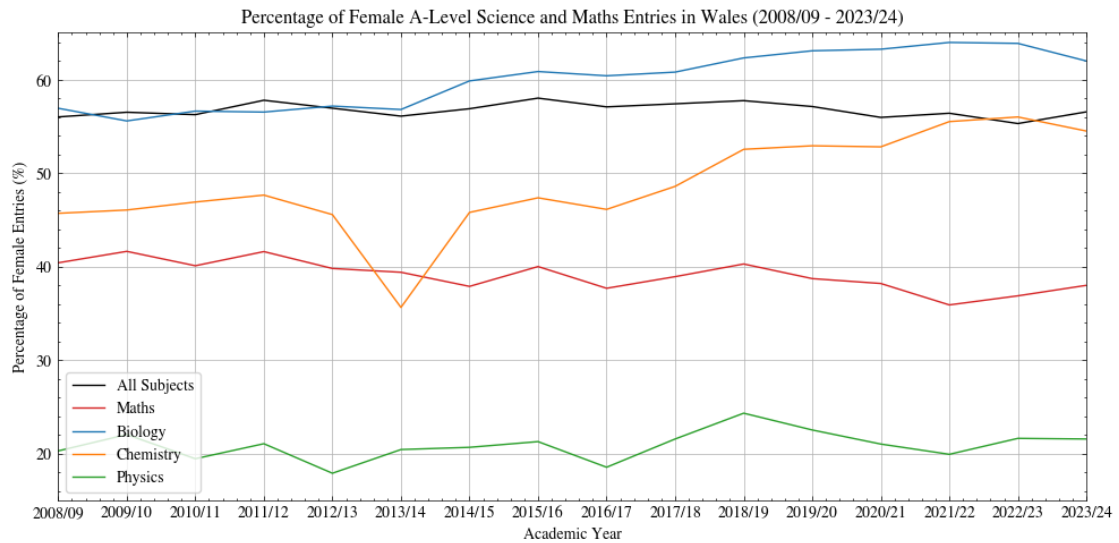


FIGURE 2.7: Percentage of female entries in A-level STEM subjects in Wales over time, including the overall yearly percentage. Data: Welsh Government (2025b).

TABLE 2.2: Percentage of A-level (for Wales and England) and Highers (for Scotland) entries in summer 2024 relative to the total number of entries for all subjects. Data credit: Welsh Government (2025b) for Wales, OFQUAL (2025) for England, and EngineeringUK (2025) for Scotland. Note, data for Scotland’s Biology uptake is not equivalent to data from Wales and England as ‘Human Biology’ is also offered and is equally popular.

Subject	Wales	England	Scotland
Biology	9.9%	8.4%	3.6%
Chemistry	7.2%	7.3%	5.0%
Maths	13.4%	12.8%	9.4%
Physics	5.5%	5.1%	4.1%

2.2 Students’ Enjoyment of Science

Numerous factors affect a student’s interest in science and future aspirations, with parental approval of science being a major factor according to DeWitt et al. (2013). Students aged 10 to 14-years old generally have high aspirations for the future (Archer Ker et al. 2013), with most aspiring to go to university and have professional careers, regardless of their background (Archer et al. 2020).

2.2.1 Attitudes towards Science

Maths is the most popular [STEM](#) subject, with 30% of students studying it at A level, while Physics has the lowest uptake of the core sciences, with 13% of students studying the subject (Archer et al. [2023](#)). Around 80% of students believe that science is relevant and practical in life, while only 68% believe the same for Maths (Archer et al. [2020](#)).

Roughly 15% of students aim to be a scientist, far fewer than the 42% of 13/14 year old students who are interested in learning more science in the future (Archer Ker et al. [2013](#)). Student aspirations to become a scientist are consistent until at least 18 years old (Archer et al. [2020](#)). Those who enjoy science are, unsurprisingly, more likely to aim for a career in [STEM](#) (Archer Ker et al. [2013](#)).

Numerous studies show that interest/enthusiasm towards science generally decreases as students age (Pell and Jarvis [2001](#); Simpson and Oliver [1985](#)), despite older students having more confidence in their scientific ability (Murphy and Beggs [2003](#)). Barmby et al. ([2008](#)) notes that this decline is greater in girls than boys. Murphy and Beggs ([2003](#)) suggests this could be due to a shift from more experimental work towards a more traditional learning environment. Baram-Tsabari and Yarden ([2009](#)) suggests that the subject of interest within science also changes as students age, shifting from enjoying topics like zoology, technology, and astrophysics to the more classical science subjects, i.e. physics, chemistry, and biology.

Bennett and Hogarth ([2009](#)) identifies that the largest decrease in positive attitudes occurs between the ages of 11 to 14, implying that the beginning of secondary school impacts the enjoyment/interest of science the most. There is also further evidence suggesting that this decrease occurs more for girls than boys (Bennett and Hogarth [2009](#)). While interest in [STEM](#) subjects decreases in primary school, there is an increase in students who have ‘strong science aspirations’ between ages 10 to 14, from 7.8% to 8.5% of students (DeWitt and Archer [2015](#)).

Students in school who are interested in science and believe they will have a career in science or engineering are almost twice as likely to complete a bachelor's degree in a science or in an engineering field (Tai et al. 2006). By nurturing interest in STEM school students, it is more likely that students will select a future in a STEM field, both at university and beyond. Conducting outreach activities for secondary school students (aged 11-18) leads to a positive increase in motivation in STEM attitudes towards a future in STEM (Vennix et al. 2018).

Physics is considered to be difficult but enjoyable (Angell et al. 2004), and classed as the 'hardest' science with the strictest grade requirements (Archer et al. 2020). Interestingly, A level Physics students are the most likely to exhibit stereotypical beliefs about scientists being 'geeky' or 'odd' (Archer et al. 2020). It is also considered to be very 'masculine' and requiring 'cleverness' (Archer et al. 2020).

Topics like space are popular with students, Williams et al. (2003) suggests that teaching science via study topics could nurture interest in the more unpopular topics of science.

While negative attitudes have negative effects on the uptake of the subject, Physics at university does have the lowest non-completion rate at 4.2% (Archer et al. 2023). This may be caused by students' negative attitudes towards Physics at school, with only those most confident in their ability applying to study it at university.

2.2.2 Conventional Lessons vs. Active Learning

Students enjoy experiments in the classroom the most compared with other aspects of their science lessons, helping students to remember and understand topics better than 'conventional lessons' (Blankenburg et al. 2016; Murphy and Beggs 2003). Studies have long identified the connection between hands-on experiments (Susiloningsih et al. 2025) and creative activities (Shanahan and Nieswandt 2009) to engage students in scientific education. Creativity is a vitally important

skill in science, but often considered to be incompatible with [STEM](#) subjects (Shanahan and Nieswandt [2009](#)).

For teachers, there is evidence that [STEM](#) workshops for young students (aged 2-5) have “significant and positive effect on participant pre-school teachers’ perceptions of early [STEM](#) practices” (Yücelyiğit [2021](#)). Improving [STEM](#) perceptions in teachers not only aids the class participating in the workshop, but also future classes who will subsequently experience the teacher’s increased enthusiasm and interest in [STEM](#) topics.

In a group taking part in interactive and active learning activities compared with those in conventional science lessons, Susiloningsih et al. ([2025](#)) found improvements in critical thinking and creativity, using pre and post-engagement tests. They also highlight the importance of using local or current themes to engage the students - in their case river conservation and renewable energy. Ensuring that students are aware of the broader context and relevance of the content also aids in the students’ learning.

Case studies by Shanahan and Nieswandt ([2009](#)) reveal that introducing creative activities to aid scientific learning reduced frustrations and increased engagement in students who struggled with conventional science lessons. This change led to better understanding and exploration of the topic in a less structured environment. Interestingly, the student in this study who enjoyed science lessons and considered herself to be stronger in scientific lessons than creative ones, struggled and found difficulty in the activities due to the difference between this and conventional lessons. The authors note that these activities could be a useful way to better this student’s creativity or their impression of their creativity in the future. This highlights the importance of introducing creative activities in [STEM](#)-based lessons/workshops as to better engage students who would not normally be interested in conventional science lessons, but ensure there is an abundance of scientific content so as not to discourage students already interested in [STEM](#) subjects.

Mansouri (2024) identifies that utilising creative activities in Physics workshops leads to better understanding and interest in science topics in female students. As women are under-represented in STEM careers, it is important to engage female students in science lessons at an early age.

Extracurricular activities can positively impact students' opinions on the subject, as studied by Jarvis and Pell (2005) following school students' visit to the UK National Space Centre. Questionnaires were distributed before, immediately after, and a while after the visit to assess the long-term effects it had. Immediately following the visit, students showed greater interest in space with a stronger belief in the value of science in society. This study also showed an increase in desire for students to work in a STEM-related field when older. This trend continues months after the trip, although, as expected, not with such a pronounced increase as immediately afterwards. There is therefore a strong indication that extracurricular activities and educational trips can have significant impressions on students.

While having benefits, one-off STEM engagements have little impact on a students' ambitions - only with longer term interventions spanning months or even years can aspirations be influenced (Archer et al. 2021).

2.3 Encouraging Engagement with Science

Engaging students with STEM is crucial in increasing the number of students opting for a career in STEM in the future. Assessing a student's background gives an indication of how they are likely to respond to along with their enjoyment of STEM lessons, but does not give the whole picture. A student's enjoyment of the subject can propel them to target a degree or career in STEM (VanMeter-Adams et al. 2014).

2.3.1 Science Capital

Archer Ker et al. (2013) introduced the concept of science capital, a measure of multiple factors which contribute to a students's exposure and awareness to science. They define it as,

“Science capital refers to science-related qualifications, understanding, knowledge (about science and ‘how it works’), interest and social contacts (e.g. knowing someone who works in a science-related job).” These factors shape a child's view and often their interest in learning about science.

Students who have high science aspirations are very likely to be male, with very high science capital; have family who use science in their jobs, and they are in the highest set in science at school (Archer Ker et al. 2013; DeWitt and Archer 2015).

Influences and attitudes of a students' family towards science have a large effect on whether a students enjoys science and/or aims for a STEM career. Involving families with ‘STEM nights’ have positive effects and motivate students with science lessons (Appel et al. 2021). Most families see the importance in their child learning about science although many have narrow views of where science can lead post-16 (Archer Ker et al. 2013).

Over 80% of students who said they have never aspired to a career in STEM have very low science capital, while 83% of those who continued with STEM post-18 have high science capital (Archer et al. 2020). Engaging students earlier in their life is positive, as those who decide on a STEM career well before they finish school are better prepared for higher education (Appel et al. 2021), and experience smoother progression (Archer et al. 2023). Between the ages of 10 to 18, career aspirations remain consistent in regard to STEM or non-STEM jobs, with those with low science capital and no interest in science, by the age of 10, being unlikely to develop STEM aspirations by age 14 (Archer et al. 2020; Archer Ker et al. 2013). It is also known that young students form an answer to the question ‘Who does science?’ very early on (DeWitt and Archer 2015),

therefore earlier interventions (and exposure to positive role models) are crucial to challenge the potentially stereotypical views students develop.

2.3.2 Under-represented Groups and Influences of Role Models

The students least likely to exhibit [STEM](#) aspirations are female, white, low science capital, lowest set in science, with no family in a [STEM](#) career (Archer Ker et al. [2013](#)). Fewer girls aspire to be a scientists than boys (12% and 18%, respectively) (Archer Ker et al. [2013](#)). Girls who consider themselves ‘girly’ are also less inclined to aim for a [STEM](#) career, and if there was an interest in science at a younger age this is usually lost over time (Archer Ker et al. [2013](#)), in addition to downplaying their femininity to fit into Physics (Archer et al. [2020](#)).

Those from disadvantaged socio-economic backgrounds are over two times less likely to study triple science at school than those from the most privileged backgrounds (Archer et al. [2020](#)). This is a trend seen for both [STEM](#) and non-[STEM](#) degrees, and there is a lower uptake for all undergraduate degrees from students from socially deprived backgrounds, with the lowest [STEM](#) subject uptake being Physics, where only 10.4% of students are from these backgrounds (Archer et al. [2023](#)).

Most students (80%) believe that scientists are ‘brainy’, which puts off students who do not consider themselves such, leading to difficulty imagining themselves in such roles (Archer Ker et al. [2013](#)). Concerns about being ‘intelligent enough’ are common even among high achieving students, and this is especially an issue for young women and in Physics (Archer et al. [2020](#)).

Issues which hinder students’ interest and desire to pursue a career in [STEM](#) are amplified in Black students (Archer Ker et al. [2013](#)).

Introducing students to role models allows the students to see themselves in [STEM](#) careers (Appel et al. [2021](#)). Gladstone and Cimpian ([2021](#)) identify 4 key recommendations for a role model to be most effective.

1. Role models must be seen as competent and successful.
2. They must be similar to the students.
3. Role models from under-represented groups have broadest appeal.
4. Their success must be viewed as attainable.

These factors contribute to maximise the influence role models can have, especially for students in under-represented groups in [STEM](#).

Role model have a broad appeal and influence on students regardless of their age (Gladstone and Cimpian [2021](#)), especially for a role model whose success is attributed to hard work and from an under-represented group (Shin et al. [2016](#)).

2.3.3 [STEM](#) Workshops

Attitudes towards [STEM](#) improve following attendance at workshops, with no difference due to a participant's gender (Timur et al. [2020](#)). To engage students with science, workshops have been found to be effective in reaching students in under-represented groups (Appel et al. [2021](#)). Sahin et al. ([2013](#)) and Vennix et al. ([2018](#)) note that students prefer workshops and projects over 'normal' science lessons as they encourage collaboration and flexibility in solving problems. [STEM](#) workshops also aid teachers as they provide opportunities to expand their knowledge and experiences on how to implement [STEM](#) practices in the classroom (Yücelyiğit [2021](#)).

Those taking part in outreach programmes have very positive views on their learning environment, which increases self-motivation in science lessons (Mateos-Núñez et al. [2020](#); Vennix et al. [2018](#)). Self-perception and self-efficacy towards

STEM increases following attendance at workshops, and could increase the number of students who desire a career in STEM (Appel et al. 2021). They allow students to view themselves as STEM professionals, and can reinforce their belief that their STEM career goals are attainable (Appel et al. 2021), in addition to emphasising positive attitudes of social implications of STEM topics (Vennix et al. 2018).

Workshops are more effective when aimed at younger students. This also increases the number of students interested in STEM in their early academic life (Appel et al. 2021), with younger students having more positive opinions on STEM than older students (Timur et al. 2020). In the short term, ‘normal’ STEM lessons have a similar short-term impact to STEM workshops, while workshops have a sustained impact over a longer period (Mateos-Núñez et al. 2020).

Having personal relevance or involvement in a topic has also been observed to increase self-motivation in STEM (Vennix et al. 2018).

2.4 Comet Chasers

Comet Chasers is an educational outreach programme utilising the ‘wow’ factor of space to develop school students’ key skills. The primary aim is to involve schools in a collaborative STEM project, reflective of how real science is conducted, rather than book learning, by connecting students with professional and amateur astronomers. Students aid in research by requesting images of comets and asteroids using the Las Cumbres Observatories network.

Activities touch on a wide range of skill, e.g. problem solving, communication, teamwork, numeracy, and critical thinking skills. Additionally, skills not usually associated with STEM education in school are given focus, e.g. Literature and creativity.



FIGURE 2.8: Presentation at beginning of a Comet Chasers workshop.

2.4.1 Classroom Activities

Numerous activities are available for teachers to use (and borrow equipment if required), touching on a range of core astronomy topics. Workshops generally begin with a brief presentation, explaining the basics of comets and why they are important to observe.

2.4.1.1 IR Cameras

Students are first introduced to the idea that everything emits infra-red light, and that hotter objects emit more. The concept of ‘seeing’ heat is something that is not intuitive if they have not encountered it before. Many students are familiar with [Infrared \(IR\)](#) cameras in the form of ‘night vision cameras’ from popular media.

Students are given freedom to explore their classroom to investigate what is hot and cold. Often, they notice radiator pipes glowing, people with glasses look like they are wearing sunglasses, or how computer equipment emits heat. In all cases, this is an unfamiliar view of a familiar environment, and immediately challenges their preconceptions.

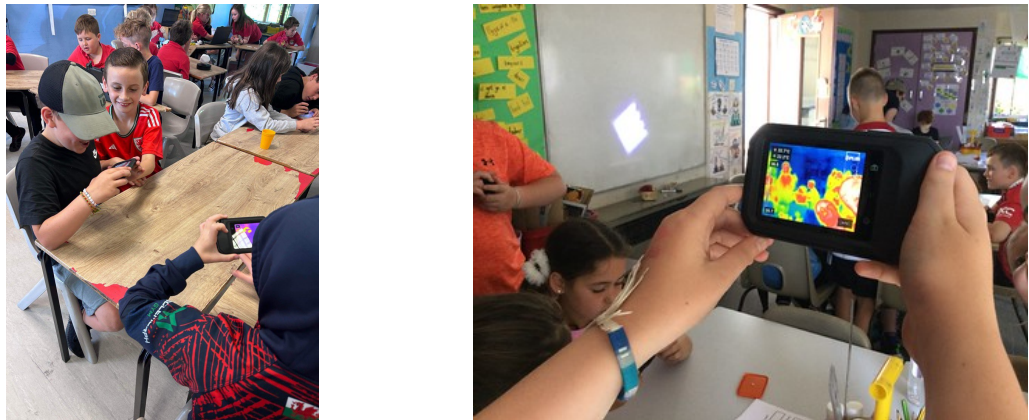


FIGURE 2.9: Students using IR cameras during Comet Chasers workshops.

Worksheets were distributed to guide the students to investigate IR light and make them ask questions about it - see worksheets in appendix 10.2. Additional activities included:

- See how heat from bodies can be transferred into other objects: like seeing a handprint on a table.
- Investigate materials which block IR light such as an emergency foil (Mylar) blankets and glass.
- Identify from two (visibly) identical water bottles as to which one contains hot water.

These activities and the excitement of using ‘specialist equipment’ gives students an insight into how we can use light to measure the temperature of objects in space (and on Earth).

2.4.1.2 Meteorite Handling

Thanks to previous STFC public engagement funding (as part of the Down2Earth project) Cardiff University has access to a large supply of meteorites and fossils. These are able to be touched and assessed/studied by students, and this is very often the first time they have held a meteorite.



FIGURE 2.10: Students interacting with meteorite samples in Comet Chasers workshops.

Students were asked to perform simple experiments on these samples, such as feeling its weight; testing if it is attracted to a magnet, and making visual observations (shape, size, colour etc.). These investigations give students an indication of what they are made of. Deliverers of the workshop then explain interesting facts about the samples, such as the age, where they were found, or in the case of tektites, how they are formed. Often, investigations of these samples were used in conjunction with [IR](#) cameras and the Rotato experiment as part of a small carousel of activities that students worked their way around.

2.4.1.3 Rotato

The *Rotato* experiment (name originated from a ‘rotating potato’ due to their similarity to asteroids), devised by Paul Roche and Helen Usher, aims to visually show students how rotational lightcurves can be formed by measuring minute changes in reflected light from an object. For asteroids and comets with lower levels of activity, this is a very useful tool to estimate colour variations, size, and shape of an object.

In this experiment, an object is placed on a turntable (a penguin is used in [fig. 2.11a](#) as it has areas of high contrast), and this object represents the asteroid/-comet nucleus. A torch is pointed at the rotating object and represents incident sunlight. This light is reflected and measured by a webcam using custom-written

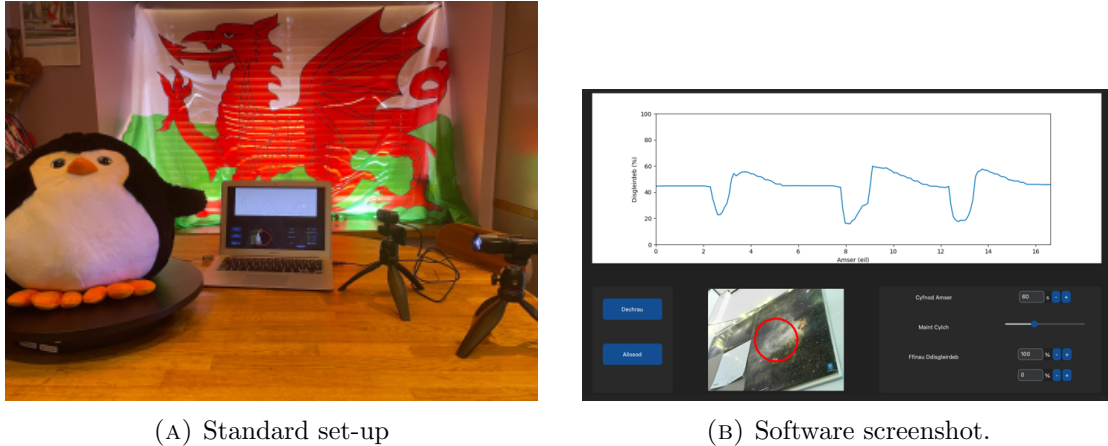


FIGURE 2.11: Main components of the Rotato experiment setup.

software produced by the author to produce a ‘live lightcurve’ of the reflected light over time. Students can then test different objects to investigate how varying colours, sizes, and shapes can affect the lightcurve produced. The lightcurve will repeat periodically, creating an identifiable pattern which can be further analysed by the students.

For example, the rotating penguin would produce a lightcurve which fluctuates from high intensity of reflected light (when the camera sees the white belly area), to a much lower intensity of reflected light (when the camera sees the black areas). This produces an almost sinusoidal curve which clearly shows how colours reflect light differently.

While useful for explaining minor-body astronomy, it has also been adapted to display how exoplanet transit curves can be produced, by replacing the object with a light source (stars) and an object ‘orbiting’ it (exoplanet). As the ‘planet’ passes in front of the light source, a slight dip in the intensity of the detected light is observed, mimicking an exoplanet transit observation.

2.4.2 Student Observations

As part of the Comet Chasers programme, schools are given access to the [Las Cumbres Observatories \(LCO\)](#) world-wide network of robotic telescopes. Suggestions are given as to which target would be best to observe, for both visibility

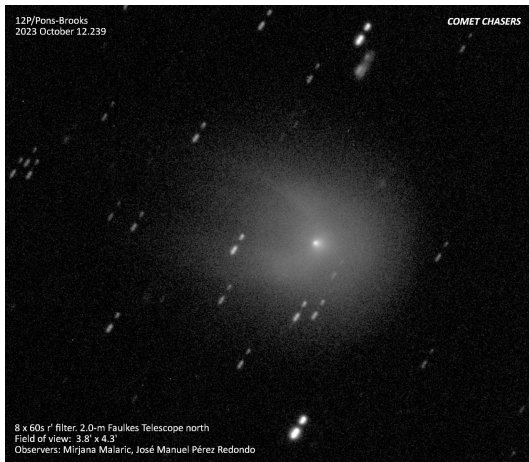


FIGURE 2.12: Students participating in the Rotato experiment during Comet Chasers workshops.

purposes and to best complement current research.

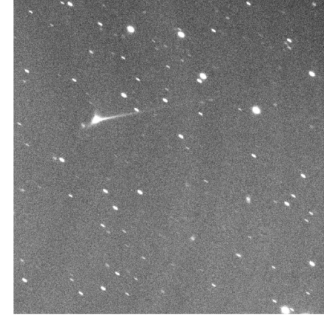
To date, more than 12 research journal publications have acknowledged Comet Chasers schools' contributions towards their research. Multiple publications include teachers/teaching assistants from participating schools as co-authors, and all list the schools in the Acknowledgements. Involving students in imaging minor-bodies as part of active research programmes is a great way to increase the number of observations made for a given object. Examples of some current publications, [Astronomer's Telegrams \(ATels\)](#) and online articles that include Comet Chasers' observations (by target) are:

- 12P/Pons-Brooks



(A) 12P/Pons-Brooks

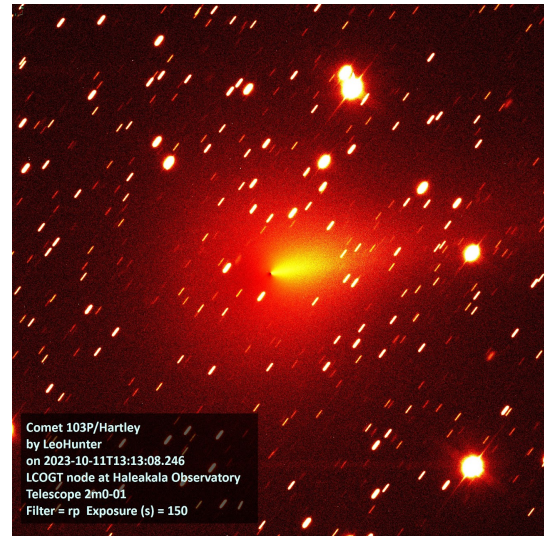
Image of Asteroid 65803 for NASA DART Mission
By St Marys Bridgend
on 2022-10-05T15:28:58.355
At LCOGT node at Haleakala Observatory
Telescope 2m0-01
Filter = rp Exposure time (s) = 60



(B) (65803) Didymos



(C) M42



(D) 103P/Hartley

FIGURE 2.13: Examples of observations made by schools taking part in the Comet Chasers programme using the LCO global network of robotic telescopes, controlled from their classrooms.

- Usher et al. (2023a)
- Kelley et al. (2023b)
- Usher et al. (2023b)
- Baker (2023)
- Ferrellec et al. (2024)
- (65803) Didymos
 - Kareta et al. (2023)

- Lister et al. ([2024](#))
- 3I/ATLAS
 - Cordiner et al. ([2025](#))
 - Santana-Ros et al. ([2025](#))
- 67P/Churyumov–Gerasimenko
 - Kelley et al. ([2021b](#))
- (248370) 2005 QN₁₇₃
 - Hsieh et al. ([2021](#))
- 7P/Pons–Winnecke
 - Novichonok et al. ([2024](#))
- C/2025 K1 (ATLAS)
 - Bodewits et al. ([2025](#))
- C/2014 UN₂₇₁ (Bernardinelli–Bernstein)
 - Roth et al. ([2025](#))
- C/2024 S1 (ATLAS)
 - Manzini et al. ([2024](#))
- C/2023 RS₆₁ (PANSTARRS)
 - Kelley et al. ([2025](#))
- 29P/Schwassmann–Wachmann 1
 - Miles ([2024b](#))
- Multiple targets
 - Kelley et al. ([2022](#))

Note, schools taking part in questionnaires for this thesis did not schedule and make observations. These workshops were treated as an introduction to the programme, with the aim of involving these schools in the observing process if they wish to continue with Comet Chasers.

Telescope observations from schools taking part in the Comet Chasers programme did contribute to the dataset that this thesis uses.

2.5 Assessment Methods

Ethical approval was obtained from The School of Physics and Astronomy Research Ethics Committee (PHYSX SREC). Initially, approval was granted based on an opt-in system, whereby guardians needed to sign a consent form, enabling their child to complete surveys and contribute to the research. Following discussion with Moore (2024), it was decided that an opt-out consent system would be simpler for teachers distributing the required information, and likely lead to an increased respondent rate (Liu et al. 2017). This reworked plan was submitted to the PHYSX SREC in early 2024, and was able to be implemented for school interventions following this date.

Consent forms were distributed at least 2 weeks prior to an intervention thus allowing teachers sufficient time to distribute and collect the signed consent forms (pre-2024) or given an opportunity to opt-out (post-2024), see appendix G. Furthermore, teacher consent forms were obtained to confirm the school's participation in the study along with their agreement to distribute the required information to guardians, see appendices E and F.

2.5.1 Surveys

Surveys, before and after interventions, were desired to assess a student's attitude towards STEM subjects, and how they responded to and enjoyed the Comet Chasers workshop.

Pre-engagement surveys, see appendix H, focused on their interest in science lessons; any personal connections to someone working in a STEM field, their dream job, and brief demographic questions. This aimed to assess a students' science capital, and to investigate if their desired job was related to their favourite subject in school.

Following interventions, students were asked to complete a survey, appendix I, based on their feelings and enjoyment of the activities conducted during the workshops. There were sections dedicated to meteorite handling, IR cameras, and the Rotato experiment, as well as their overall opinions on the workshop.

2.5.2 Survey Analysis

The majority of questions use a pie chart to display the responses. This is best used for closed questions, making it easier to see the proportion of answers. Pie charts present yes/no question results.

Some questionnaire questions will ask students to rank their opinions on a numerical rating scale: a Likert-type question to assess their fondness of a subject. Analysing these responses is not as straightforward as expected. The average value does not discern anything too useful as the ends of the scales are contradictory. Numerous analysis methods are used to give a better overview of the responses, in addition to displaying a diverging stacked bar chart, as suggested by Heiberger and Robbins (2014). Weighted average, mode, and median are calculated for each question.

The weighted average is calculated via,

$$\text{Weighted average} = \frac{\sum (Wn)}{N} \quad (2.1)$$

where W is the weighing factor (the number used to rank in these instances), n is the number of responders who selected that rank, and N is the total number

of responders. For our purposes, this equation will be,

$$\text{Weighted average} = \frac{5n_5 + 4n_4 + 3n_3 + 2n_2 + n_1}{N} \quad (2.2)$$

where n_x is the number of responders who selected value x for that question.

Weighing the average is important as it better represents a distribution, unless there are extremes in the data, which can skew it (Chakrabartty 2014; León-Mantero et al. 2020; Tastle et al. 2008).

Additionally, the median and mode are calculated for Likert-type responses.

Net Promoter Score (NPS) is also calculated to find the overall positive/negative opinion of the surveyed population. This is a quantity used primarily in market research to assess a percentage of customers who would promote a company (Owen 2019). In this study, for a response which is ranked using 1 to 5 scale, responses of 4 and 5 are considered promoters, while responses of 1 or 2 are considered demoters. This is calculated using,

$$NPS = \left(\frac{n_4 + n_5}{N} \right) - \left(\frac{n_1 + n_2}{N} \right) \quad (2.3)$$

where N is total number of responses, and n_i is the number of responses who selected i rank.

While **NPS** is predominantly used in business contexts in regards to customer loyalty, it has been used in educational contexts to assess student satisfaction of programmes attended (Figueroa-Ochoa et al. 2025; Gamarra-Moreno et al. 2021; Kara et al. 2024; Lucero 2022).

NPS does not measure knowledge retention nor learning outcomes of educational programmes, instead, it treats schools and students as customers to assess their likelihood of continuing and promoting the Comet Chasers programme. This satisfies the aim of this study, as to assess a school's introduction into the Comet Chasers programme, before taking part in more in-depth astronomical research. Additionally, **NPS** is a straightforward yet effective measure for measuring student satisfaction (Kapi et al. 2025).

Hrastinski et al. (2021) and Rengifo-López et al. (2024) use NPS scores to assess satisfaction in different educational programmes aimed at school-aged students, investigating opinions on workshops and future educational ambitions. Similarly, Cruz et al. (2019) investigates how undergraduate engineering student satisfaction varies between cohort groups and between different aspects within the course. Using NPS provided a clear and concise measure to track changes made to the educational programme over time. These studies are comparable with this (pedagogical) study as they explore satisfaction rather than learning outcomes from the student's perspective, allowing refinement of the programme in any future iterations.

The small sample size of this study could affect the NPS, as it would be more sensitive to changes. However, it is considered to be a fair measure to present, especially in conjunction with the weighted average, mean, median, and mode, to display the satisfaction of the students with the different workshops.

Where applicable, the statistical significance of different year groups was calculated using the non-parametric Kruskal-Wallis test (Tsarev et al. 2025). This test assesses whether the null hypothesis (i.e. all groups have equal medians) should be accepted between 3 or more independent groups. This allows investigation if year groups have statistically different opinions on the activities. All observations in the dataset were ranked. As the data were collected using a Likert scale, tied values were assigned the average of their corresponding ranks.

Following ranking, the H statistic is calculated using,

$$H = \frac{12}{n(n+1)} \sum_{j=1}^C \frac{R_j^2}{n_j} - 3(n+1) \quad (2.4)$$

where n is total number of responses, C is the number of independent groups, R_j is the sum of scores in the j th group, and n_j is the size of the j th group. This metric can then be compared with the χ^2 for a given the desired significance level and degrees of freedom - in this case a significance level of 5% and 2 degrees of freedom due to 3 year groups surveyed. If $\chi^2 > H$, then the null

hypothesis is maintained, suggesting that there is not statistical difference between the year groups' responses, while $\chi^2 < H$ means the null hypothesis can be rejected.

To assess the size measure difference if the null hypothesis is rejected, η_H^2 is used which can be calculated using,

$$\eta_H^2 = \frac{H - C + 1}{n - C} \quad (2.5)$$

$\eta_H^2 \geq 0.01$ representing a small change, $\eta_H^2 \geq 0.06$ representing a medium change, and $\eta_H^2 \geq 0.14$ representing a large change (Fiel Peres 2025).

For open questions, students are asked to type in their response, giving greater freedom in expressing their feelings without potentially asking leading questions. Qualitative data is more difficult to analyse, and more unfamiliar to the author, than quantitative data - care must be taken to ensure that the respondent's true emotions are not misrepresented when the data is collated in a more concise and readable way. Due to the variation in responses, thematic analysis was conducted to categorise their responses.

Thematic analysis is the act of identifying overarching themes or ideas and categorising them as to identify repeated patterns that may arise (Castleberry and Nolen 2018; Kiger and Varpio 2020; Lochmiller 2021). The themes detected can be used with demographic data to allow an investigation into the respondents' beliefs and where these may have originated (Clarke and Braun 2017).

For our purposes, thematic analysis will help identify which aspects of Comet Chasers' activities the students like or dislike, and what they learn. All responses were categorised into general themes, with some responses straddling multiple groups. These general categories are displayed in a pie chart and categories discussed, while quoting the responses directly.

Chapter 3

Cometary Science Introduction

“It is necessary to have a record of the rising of comets in times past. Because of their rarity, their path cannot yet be understood, nor can it be determined whether they maintain sequences and whether a definite pattern causes them to reappear at a particular time.”

Séneca

Comets are some of the most primitive objects in the [Solar System \(SS\)](#) (Marboeuf et al. [2012](#)), the unused bodies cast away during planetary formation. Investigating these objects can provide explanations to the early [SS](#) and to the [SS](#)’s evolution.

3.1 Comet Basics

3.1.1 Ancient Cometary Astronomy

Both fascinating and fearing to our forefathers, comets have always been looked upon with great mystery. Often seen as deadly omens, they were considered of

great significance and believed to be predictors of great disasters for many cultures throughout history (Fernández 2005). Historically, numerous comet apparitions seem to coincidentally occur around the times of great tragedies - although when in history has there been an period where no catastrophes occurred (Lewis 1997)?

The earliest surviving, reliable record of a comet apparition is from 674 BCE: a Babylonian stone tablet (Fernández 2005). However, it is believed that the first recorded observation of a comet was in the third millennium BCE by the Chaladeans, living in an area in modern day Iraq (*A History of Comets - Part 1 From Harbingers of Doom to Celestial Wanderers* 2019).

Chinese civilisations recorded comets meticulously against the stars (Whipple and Green 1985). Until the 1700s CE, Chinese astronomers produced the most reliable, conclusive and coherent records of comet apparitions (Fernández 2005). The most significant Chinese record is ‘The Mawangdui Silk Texts’, an almanac written in the fourth century BCE, recording observed comets from the 11th century BCE (*A History of Comets - Part 1 From Harbingers of Doom to Celestial Wanderers* 2019). This text provided astrometry and details of the comet’s appearance next to corresponding catastrophes that were believed to have been caused by the comet (*A History of Comets - Part 1 From Harbingers of Doom to Celestial Wanderers* 2019).

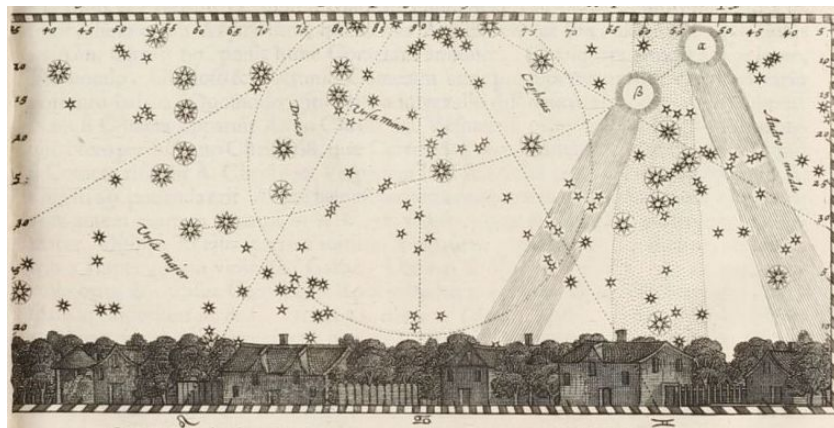


FIGURE 3.1: Diagram from *Historia Cometarum* where showing cometary position compared to the stars. Credit: Lubieniecki (1666).

Often, we can deduce how ancient people and societies viewed comets by examining the terms used to name and describe them. Ancient Chinese people called them ‘broom-stars’ or ‘sparkling star’ due to their appearance (Fernández 2005), while the Greeks adopted ‘kometes’, meaning ‘long-haired’ stars, originally from the Egyptians (Whipple and Green 1985). More aggressive language was used by other civilisations, naming comets after axes, scimitars, swords or daggers, representing the death and devastation comets were believed to be the fulfilment of ancient prophecies (Whipple and Green 1985). Even the word we use today for an appearance of a comet, ‘apparition’, is rooted in fear, as it invokes a supernatural or ghostly image (Fernández 2005).

3.1.2 Halley’s Comet

Edmond Halley (1656-1742) worked closely with Isaac Newton throughout his later career, as well as Robert Hooke and Sir Christopher Wren, who all tried to unlock what keeps planets in stable orbits (Eggen 2025). Newton was the first to decipher the gravitational mystery, and was encouraged and funded by Halley to publish his findings in the *Principia* (Eggen 2025).

Using Newton’s breakthrough in orbital mechanics, Halley proceeded to examine any records of comet apparitions available to him, in order to better understand them (Lewis 1997). Halley published *A Synopsis of the Astronomy of Comets* in 1705 detailing the parabolic orbits of 24 comets, observed between 1337 to 1698 (Eggen 2025). The comets observed in 1531, 1607 and 1682 all seemed to have similar characteristics, leading Halley to believe they were the same body returning while orbiting the Sun (Eggen 2025). The orbital period of the comet was not consistent, with periods ranging from 75 to 78 years. Halley suggested that this discrepancy was due to perturbations by the giant planets as the comet passes them, deviating the object from its original trajectory (Lewis 1997). Using this information, Halley predicted that the comet would return in 1758 (Lewis 1997). His hypothesis was correct, the comet did return that year. Unfortunately, Halley died in 1742, never being able to witness if his

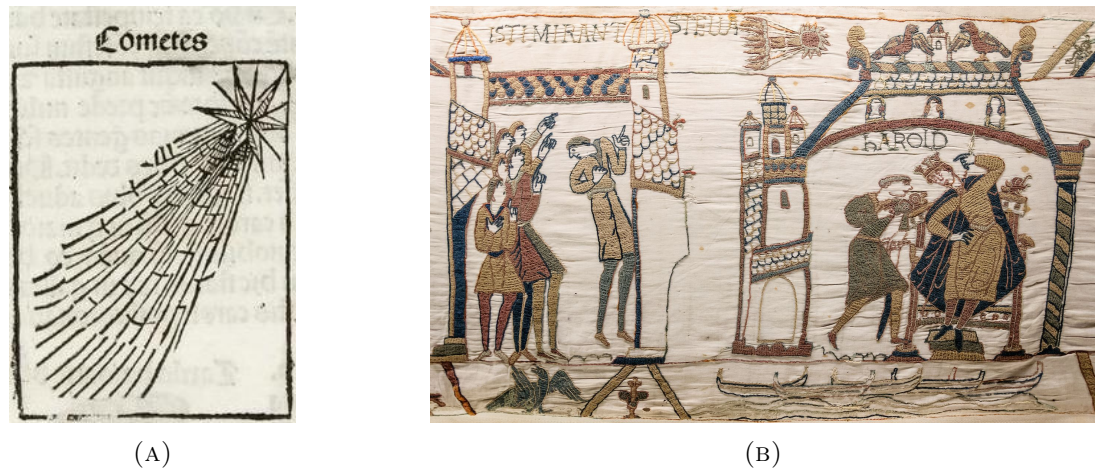


FIGURE 3.2: [a](#) Illustration of what is believed to be Halley's comet's apparition in 66 CE, depicted in the Nuremberg Chronicle (Schedel [1493](#)) [b](#) Halley's Comet embroidered above the doomed king: Harold Godwinson (*Bayeux Tapestry* [1070](#)).

breakthrough prediction came to fruition. In his honour, the comet was named after him, as Halley's Comet. This began the tradition of naming comets after their discoverer or the people who first postulated the object may be returning (in the case of Halley).

We now know Halley's orbital period estimate was accurate, as it has an orbital period of 75.32 years (Giorgini and Group [n.d.](#)).

Since his breakthrough, Halley's Comet has been identified in historical records from 240 BCE (potentially as far back as 1614 BCE) in Chinese records (Whipple and Green [1985](#)). In 66 CE, it was seen 4 years before the destruction of Jerusalem by Emperor Titus, and it was depicted in the Nuremberg Chronicle in 1472, as seen in [fig. 3.2a](#) (Lewis [1997](#)). Halley's comet most famous historical depiction is probably in the Bayeux Tapestry, a 70m long embroidered cloth displaying the events leading up to the Battle of Hastings in 1066, [figure 3.2b](#) (Lewis [1997](#)). Again, the comet was seen as a deadly prophecy for Harold Godwinson (who was killed at the Battle of Hastings). The irony being that William the Conqueror must have also seen the comet, but he survived.

Halley's comet was last seen with the naked eye from Earth on October 16, 1986, with its next apparition due to reach [perihelion](#) on July 28, 2061 (Giorgini



FIGURE 3.3: Colour image of Halley's Comet during its last apparition in 1986. Credit: W. Liller, Easter Island

and Group [n.d.](#)).

3.1.3 Post-Halley Era

We consider modern cometary astronomy as research conducted since Halley's discovery of comet orbital dynamics. Since Halley, comets have been rigorously observed and documented. These campaigns usually centred around observations as comets pass the Earth closely, or due to unique interactions with other bodies.

Both Halley's Comet and comet Hale-Bopp (C/1995 O1) were visible in the sky in the late 20th century. Hale-Bopp was visible to the naked eye for 18 months between 1995 and 1996, at a large [heliocentric](#) distance, greater than 7 AU, due to a very large nucleus, diameter $d = 60$ km (Bailey et al. [1996](#); [Small-Body Database Query n.d.](#)). It is considered one of the most observed comets, with polls suggesting 81% of the US adult population having seen it (Aguirre [1997](#)). Astronomers thoroughly analysed the object and discovered a very high dust

production rate at roughly $1.8 \times 10^6 \text{ kg s}^{-1}$ (Jewitt and Matthews 1999), suggesting that this may have been only the second time the comet entered the inner SS (previously passing the Earth in 2215 BCE) (Marsden 1997).

Modern telescopes and [Charged-Coupled Devices \(CCDs\)](#) allowed the observation of comet Shoemaker-Levy 9's (D/1993 F2) destruction and subsequent impact into Jupiter in 1994 - the first observation of two SS objects colliding (Williams 2005). Utilising ground-based observations and numerous space-based observatories, astronomers had a detailed view of this unique event. This analysis supports the theory that Jupiter may play a major part in capturing minor-bodies from entering the inner SS, which may have allowed the Earth enough time without major impacts to allow life to flourish.

More recently, the first interstellar object was detected, designated 1I/'Oumuamua (1I/2017 U1). While initially thought to be a comet, no coma was detected, resulting in the object being designated an interstellar asteroid (Meech et al. 2017). Two years later, an actual interstellar comet was discovered, 2I/Borisov (Borisov 2019), this time presenting a coma (Fitzsimmons et al. 2019). In 2025, a third interstellar object has been detected - a comet: 3I/ATLAS. Detected by the ATLAS survey telescope, it reached [perihelion](#) in October 2025 (Farnocchia 2025).

As of April 2022, 4404 comets have been discovered ([Minor Planet Centre - Home n.d.](#)).

3.1.3.1 Spacecraft Missions to Comets

The first flyby of a comet was in 1985 by the [International Cometary Explorer \(ICE\)](#) (formerly 'International Sun-Earth Explorer 3'), launched by NASA in cooperation with ESA in 1978, with its primary mission to conduct a deep survey of the solar wind interactions with the Earth's magnetic field. Following the primary mission's success, two comets were selected for flybys, 21P/Giacobini-Zinner (passing within 7,862 km in 1985) and 1P/Halley (passing 40.2 million

km in 1986) (Siddiqi 2018). The spacecraft measured 21P/Giacobini-Zinner's magnetic field formed due to the solar wind (Farquhar 2001).

During Halley's comet's 1986 apparition, numerous flyby missions were conducted to carry out scientific observations of and near the comet, ran by numerous countries and organisations such as the USA with ICE), USSR with Vega 1 and 2 (producing the first in-situ image of a comet (Ulivi and Harland 2007)), Japan with Suisei and Sakigake and ESA with Giotto, figure 3.4 shows the image taken by Giotto in 1986 (Keller et al. 2004). These missions were known as the Halley Armada, providing the first multi-mission in-situ observations of a comet.



FIGURE 3.4: First close-up, colour image of Halley's comet's nucleus taken by ESA spacecraft Giotto using the Halley Multi-colour Camera in 1986. Credit: ESA/MPAe Lindau (2011).

Since the 1980s, there have been many missions to comets, including NASA missions Deep Space 1 (DS1), Stardust, and Deep Impact and most recently ESA mission Rosetta.

Initially, DS1's mission was to test new technologies, such as the use of an ion engine for space propulsion (Deep Space 1 2025). DS1 exceeded its initial mission plans and proceeded to take highly detailed images of comet 19P/Borrelly and asteroid 9969 Braille (Deep Space 1 2025).

Conducting a flyby of both comets 81P/Wild and 9P/Tempel, Stardust aimed and succeeded to return a cometary sample back to Earth (Stardust 2025). Comet and interstellar dust was collected in aerogel during the flyby of 81P/Wild, analysis suggested it contained ejected materials from the early stages of the Sun's

formation, leading researchers to believe that the Sun may have formed in a different manner than originally thought ([Stardust 2025](#)).

Deep Impact was the first mission to land an impactor probe on a comet's surface (9P/Tempel) exposing materials underneath the nucleus' crust ([Deep Impact 2025](#)). Large amounts of organic materials along with water ice were detected under the surface ([Deep Impact 2025](#)).

Rosetta, an ESA mission with contribution from NASA, was originally planned to become the first orbiter of a comet and conduct the first soft landing on a comet with its lander, Philae (ESA [n.d.](#)). Rosetta reached comet [67P/Churyumov-Gerasimenko \(67P/CG\)](#) in August 2014, landing Philae successfully, albeit a bumpy landing, in November 2014 (ESA [2025](#)). This mission provided the most detailed images of a cometary nucleus, while also identifying that the nucleus is more porous and dustier than previously expected (Fulle et al. [2016](#)).

In the near future, the Comet Interceptor mission aims to launch, led by ESA with support from JAXA. This mission is unusual as the target is not yet decided, and may not have even been discovered yet. It aims to investigate dynamically new comets, objects incoming into the inner Solar System for the first time (Jones et al. [2024](#)). The spacecraft will remain at the Sun-Earth Lagrange Point 2 while a suitable target is identified. Comet Interceptor will allow a detailed observation of a 'pristine' comet sample, before it is heavily tainted by solar radiation.

3.1.4 Comet Structure

Both Aristotle and Galileo believed comets were a phenomenon forming in the Earth's upper atmosphere (Heidarzadeh [2008](#)). Since Halley's research, hypotheses regarding the creation of comets, and thus structure, shifted from a mirage to extra-terrestrial origins (Lyttleton [1948](#)).

The rough structure of comets (i.e. nucleus, coma, tails) has been well-documented since the mid-1800s, "The principal part of their structure is the head, which

presents the appearance of a nebulous body, more or less condensed towards the centre. Within the head a bright point is seen, approaching in lustre to a planet. This is called the nucleus of the comet. The nebulosity of the head is surrounded by a hazy contour, termed the coma. But the most remarkable part in the structure of a comet is the tail, which appears as a long train of light issuing from the head.” (Grant 1852).

Numerous models have been proposed in an attempt to explain the structure of comets and how they are formed. Today, we have a clearer understanding of comets due to enhanced and more regular observing and, more importantly, in-situ observations and measurements.

3.1.4.1 Flying Sandbank/Lyttleton’s Accretion Theory

In 1948, Lyttleton proposed that comets were formed when the Sun passed through a cloud of interstellar dust, causing the dust particles to converge along a line following the Sun in its relative motion and colliding to form coherent bodies with embedded gases, see figure 3.5, he called this body ‘flying sandbanks’ (Whipple and Green 1985). Lyttleton proposed that several thousand comets could be formed by a single passage of the Sun, and that the giant planets’ gravity ensured that newly formed comets would have enough angular momentum to avoid falling directly into the Sun (Lyttleton 1948). Variations in comets would occur due to the Sun passing through different dust clouds throughout its life (Whipple and Green 1985).

Using comet 2P/Encke as an example, as it approaches the Sun, the coma grows to 500,000 km then shrinks to 16,000 km (Whipple and Green 1985). Lyttleton suggested the shrinkage was due to each grain in the coma being in its own orbit around the Sun, hence why the comet shrinks periodically (Whipple and Green 1985).

The main issue with Lyttleton’s model was the Poynting-Robertson Effect, discussed by Whipple when proposing his dirty snowball model (see section 3.1.4.2).

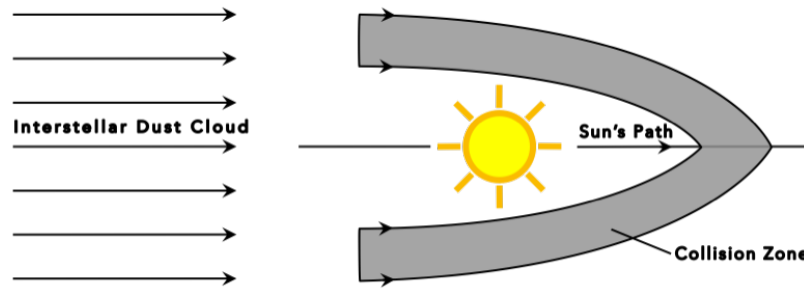


FIGURE 3.5: Diagram depicting how comets are formed according to Lyttleton's accretion theory. Interstellar dust is attracted by the Sun's gravity and converges on the path of motion. Particles collide, forming greater, coherent bodies in the grey area. Credit: Whipple and Green (1985), reproduced by Author.

This effect describes how radiation from the Sun contracts the orbits of small particles (Burns et al. 1979). After a few orbits, the smaller particles would move in smaller orbits with a shorter orbital period while larger particles would orbit in greater orbits with a greater orbital period (Whipple and Green 1985). This divergence would result in the nucleus stretching, which has never been observed (Whipple and Green 1985).

Over a long period of time, particles would continually collide into a discrete object, held together by its own gravitational force (Whipple and Green 1985). This disproves Lyttleton's theory, as its main assumption is that each particle is in its own independent orbit with little or no interaction from other particles forming the comet itself. Moreover, this model fails to explain how comets can repeatedly undergo outbursts.

3.1.4.2 Dirty Snowball v Icy Dirtball

Due to the discrepancies and issues with Lyttleton's model, Fred Whipple created his own model in 1950 which attempted to fix the issues with the flying sandbank model. In the heads of comets, the molecules CN, C₂, and radicals OH, C₃ and NH had been identified in the 1940s (Whipple and Green 1985). Positive ions, like CO⁺, CH⁺, OH⁺, NH₂⁺, and NH⁺, were also identified in the tail of comets (Whipple and Green 1985). Whipple proposed that the radicals

and ions seen in the head of the comet were from larger, ‘parent molecules’ from the nucleus (Whipple and Green 1985). For example, OH from water (H_2O), CH from methane (CH_4), NH from ammonia (NH_3) and CO from carbon dioxide (CO_2). All these larger molecules are common in the SS as they originate from the Sun and explains how comets can continue to be active for thousands of years (Whipple and Green 1985). According to Whipple, the nucleus was a large mass of ices embedded with dust or meteoric particles, hence the name ‘dirty snowball’.

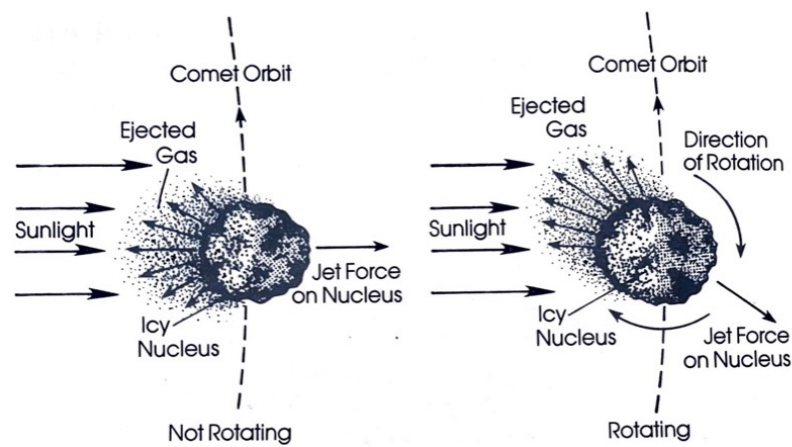


FIGURE 3.6: Diagram displaying the jet force on a comet when gas is ejected from the nucleus due to incident sunlight. Credit: Whipple and Green (1985).

Whipple’s model explains why comets activity drastically increases approaching [perihelion](#). Incident sunlight sublimates the ices in the nucleus, with the gas releasing into the coma, thus increasing the observed brightness (Fernández 2005). This [sublimation](#) causes a jet force exhibited on the nucleus, deviating the comet from its current orbit, fig. 3.6 shows the force direction relative to the direction of the incident sunlight (Whipple and Green 1985).

Following Giotto spacecraft’s encounter with Halley’s Comet during its latest apparition in 1986, Whipple’s dirty snowball melted away. The dark colour and dust production exceeded what was predicted in the dirty snowball model (Tholen et al. 1986) leading the shift to the term ‘icy dirtball’.

3.1.4.3 Current Understanding

Since Halley’s Comet’s most recent apparition, cometary astronomy has developed immensely. Numerous in-situ observations of comets and observations of the disintegration of comets has allowed astronomers to begin to unlock the structure and composition of their nuclei.

Cometary nuclei are now seen as a greater proportion of rock than ice, contrary to what was previously believed. Nuclei are highly porous (35-75% porosity), with ices and dust making up, 10-20% and 20-50% of the nucleus, respectively (Lamy et al. 2015). The assumed refractory-to-ice mass ratio, δ , of comets increased following visiting 67P/CG in 2014, with an estimate of $\delta > 3$ (Fulle et al. 2019) for most comets. This suggests that the nucleus consists mainly of a “mixture of minerals and organics with a minor mass fraction of ices mixed among them” (Fulle et al. 2016), leading to comets now being defined as “mineral organics”. Previously, cometary proportion of ices were considered to distinguish them from asteroids, which were made of mostly refractory materials. While the distinction between comets and asteroids was always somewhat ambiguous, it is now even more unclear what the structural and compositional differences between the two types of objects are. This is especially the case when considering active asteroids behaving like comets but have compositions closer to asteroids.

It is not possible to directly observe the composition of a comet’s nucleus via ground-based observations. Investigating the fragment molecules seen within comae gives an indication of their parent molecules, and thus the species present within the nucleus (Cochran et al. 2015). H_2O , CO, and CO_2 are the primary gases detected within the coma, and therefore make up the majority of the volatile ices within the nucleus (Harrington Pinto et al. 2022). These ices were able to occur within the nucleus due to the formation of the object at temperatures $T < 60$ K (Garrod 2019) in the Edgeworth-Kuiper Belt (EKB) or Oort cloud. Approximately half of comets have more CO_2 than CO in their comae, with a



FIGURE 3.7: Close up image of the nucleus of comet [67P/CG](#) during the Rosetta mission. Credit: ESA/Rosetta/MPS for OSIRIS Team MP-S/UPD/LAM/IAA/SSO/INTA/UPM/DASP/IDA ([2015](#)).

third having more CO than CO₂, while a tenth have roughly an equal proportion of both molecules (Harrington Pinto et al. [2022](#)).

Additional molecules have been identified in the comae of comets, albeit in small proportions. Methanol (CH₃OH), methane (CH₄), and ethane (C₂H₆) have been detected in numerous comets and in proportions of 2.05%, 0.72%, and 0.52% relative to water present, respectively (McKay and Roth [2021](#)).

3.1.5 Evolution

Generally, comets originate from either the [Edgeworth-Kuiper Belt](#) or Oort Cloud, regions on the edge of the [SS](#) containing primitive samples of ice-rich bodies, relatively untainted by insolation and untouched since their formation in the protoplanetary disc (Fernández [2008](#)). By analysing the composition of their

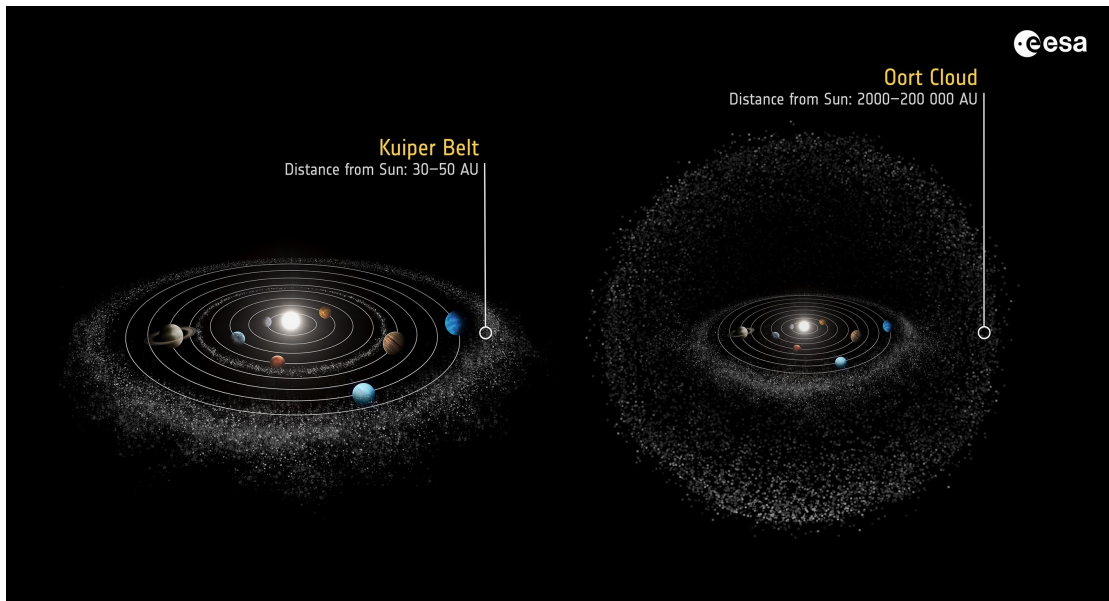


FIGURE 3.8: Diagram displaying the [Edgeworth-Kuiper Belt](#) and Oort cloud and their respective [heliocentric](#) distances. Not to scale. Credit: ESA ([2014](#)).

ices, it is apparent that comets must form at very low temperatures in order to condensate the [volatile](#) material (Marboeuf et al. [2012](#)).

The [EKB](#) has been hypothesised as the origin of comets since the mid-20th century, with [heliocentric](#) distance ranging from 30 – 50 AU (Stern and Colwell [1997](#)). This region was hypothesised by Edgeworth ([1943](#), [1949](#)) and Kuiper ([1951](#)) containing a reservoir of comet-like bodies, topping up the population of comets which enter the inner [SS](#). The [EKB](#) is believed to be the source of [Short Period Comets \(SPCs\)](#) (Fernández [1980](#)). Objects in this region are known as [Kuiper Belt Objects \(KBOs\)](#), with the first identified [KBO](#) detected by Jewitt and Luu ([1993](#)) in 1992, due to the objects' generally small size and at large [heliocentric](#) distances making them very unclear when observed from Earth. Following Pluto's reclassification from planet to dwarf planet, it has been considered a [KBO](#) due to its orbital location and similarity to other objects such as 136472 Makemake and 136199 Eris (Delsanti and Jewitt [2006](#)).

Comets can also originate from the Oort cloud, first proposed by Oort ([1950](#)). He hypothesised that this region could be the source of [Long Period Comets \(LPCs\)](#): a shell encompassing the [SS](#) at [heliocentric](#) distances of 2,000 AU up to potentially 200,000 AU (Levison and Dones [2007](#)).

Perturbations from the large planets and other objects at similar orbits can propel them into the inner [SS](#). Broadly, these objects become [SPCs](#) and [LPCs](#), see sections [3.1.6.2](#) and [3.1.6.1](#). Simulations show that [KBOs](#) which transition into comets have a median dynamical lifetime of 4.5×10^7 yr (Levison and Duncan [1997](#)).

A comet's life can end in numerous ways: loss of activity, collision/fragmentation, or expulsion.

Due to the [volatile](#) nature of materials within comet nuclei, repeated approaches to the Sun can lead to the object exhausting its supply of ices, which cause activity around [perihelion](#) (Weissman et al. [2002](#)). This results in an inert, asteroid-like object orbiting the Sun, which Weissman et al. ([2002](#)) believes could have historically been incorrectly identified as an asteroid. In the case of [JFCs](#), it is expected that the ratio of extinct to active objects is 3.5 (Levison and Duncan [1997](#)). These objects remain in their 'usual' orbit, but no longer exhibit the expected cometary activity.

A more violent end for a comet can be in the form of colliding with a planet or the Sun, fragmentation, or complete disintegration. Famously, comet Shoemaker–Levy 9 (D/1993 F2) fragmented and collided with Jupiter in July 1992, with its scars on Jupiter visible for months following impact (Harrington et al. [2004](#)), see figure [3.9](#). Impacts into Jupiter occur on an, astronomically, regular basis, believed by Levison and Duncan ([1997](#)) to occur once every 400 years, though numerous impacts have been observed in the 21st century (Hueso et al. [2018](#)).

Fragmentation can be detected due to a surge in brightness, similar to an outburst, followed by identification of fragmented pieces. Objects fragment mainly due to the tidal forces exhibited on the minor-body during close approaches to the giant planets, its own centrifugal force due to its rotation, changes in temperature (such as conversion of [AWI](#) to [CWI](#), discussed in sect. [3.4.1.1](#)), shearing of the nucleus due to a [bilobate](#) structure, or being impacted by other objects (Fernandez [2009](#); Knight et al. [2023](#)).

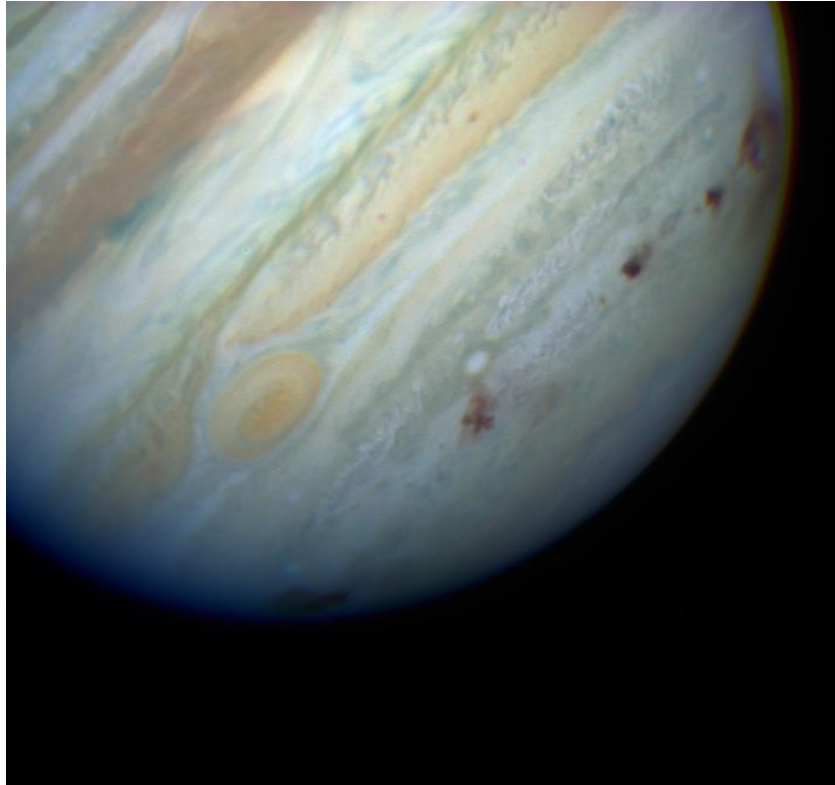


FIGURE 3.9: Aftermath of comet Shoemaker-Levy 9's highly observed impact into Jupiter. Credit: NASA ([1994](#))

Finally, a comet's orbit can be perturbed such that its orbit becomes hyperbolic, leaving the [SS](#), never to return. Comet [Bowell 1980b](#) was calculated to have an orbital [eccentricity](#) greater than 1, following a close approach with Jupiter ([A'Hearn et al. 1984](#)). The comet is currently exiting the [SS](#). Also being expelled from the [SS](#) due to their highly eccentric orbits are the three discovered interstellar objects: [1I/'Oumuamua](#), [2I/Borisov](#), and [3I/ATLAS](#). These interstellar objects were likely expelled from their original star system by the same mechanism.

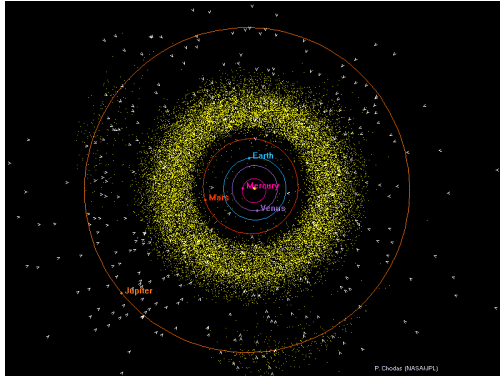
3.1.6 Comet Taxonomy

Generally, comets are separated into two main types [LPCs](#) and [SPCs](#), with orbital periods greater than 200 years and less than 200 years, respectively. Since 2017, an additional, yet rare, type is used to identify interstellar objects due to the discovery of [1I/'Oumuamua](#), [2I/Borisov](#) in 2019, and [3I/ATLAS](#) in 2025.

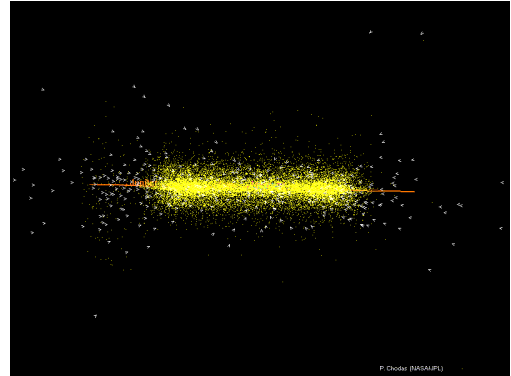
More specific comet types are used in classification and are usually based on the comet's orbital parameters. While the intention is to better categorise comets, some objects can belong to multiple types. Classification used by [JPL](#) for both comets and asteroids can be seen in figures [3.11](#) and [3.12](#).

Objects do not always lie comfortably within a single classification. Some unusual objects, like Centaurs, can be classed as different types dependent on which definition is used, more on this issue with Centaurs in sect. [3.2.4](#).

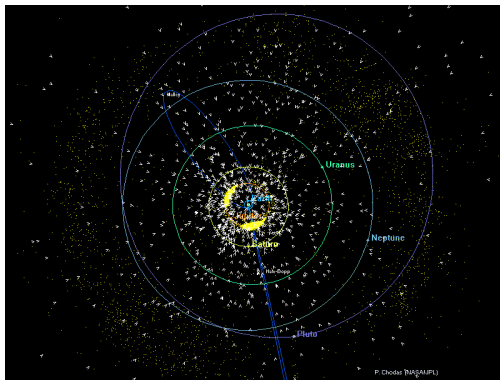
Some have suggested using a taxonomy based on the [volatiles](#) and grain structures present in the nucleus (Eisstrup et al. [2019](#); Mumma and Charnley [2011](#); Russo et al. [2016](#)). Grouping objects based on their physical properties reduces ambiguity of classification compared with orbital classifications, and better groups objects of similar origins (both age and formation location).



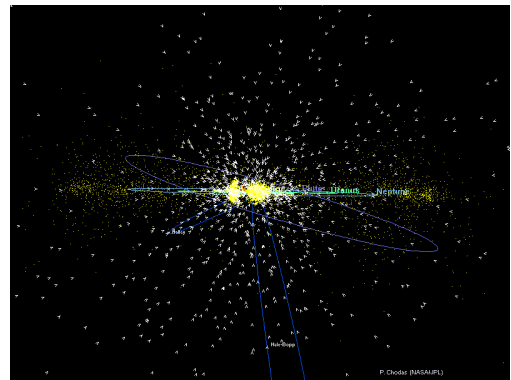
(A) Inner SS viewed from above the ecliptic plane



(B) Inner SS viewed from the side of the ecliptic plane



(C) Outer SS viewed from above the ecliptic plane



(D) Outer SS viewed from the side of the ecliptic plane

FIGURE 3.10: Diagrams showing the distribution of objects in the SS from above and side of the ecliptic plane. The planets are shown with their respective orbits with asteroids as yellow dots and comets as chevrons pointing towards the Sun. Credit: Chodas (2018)

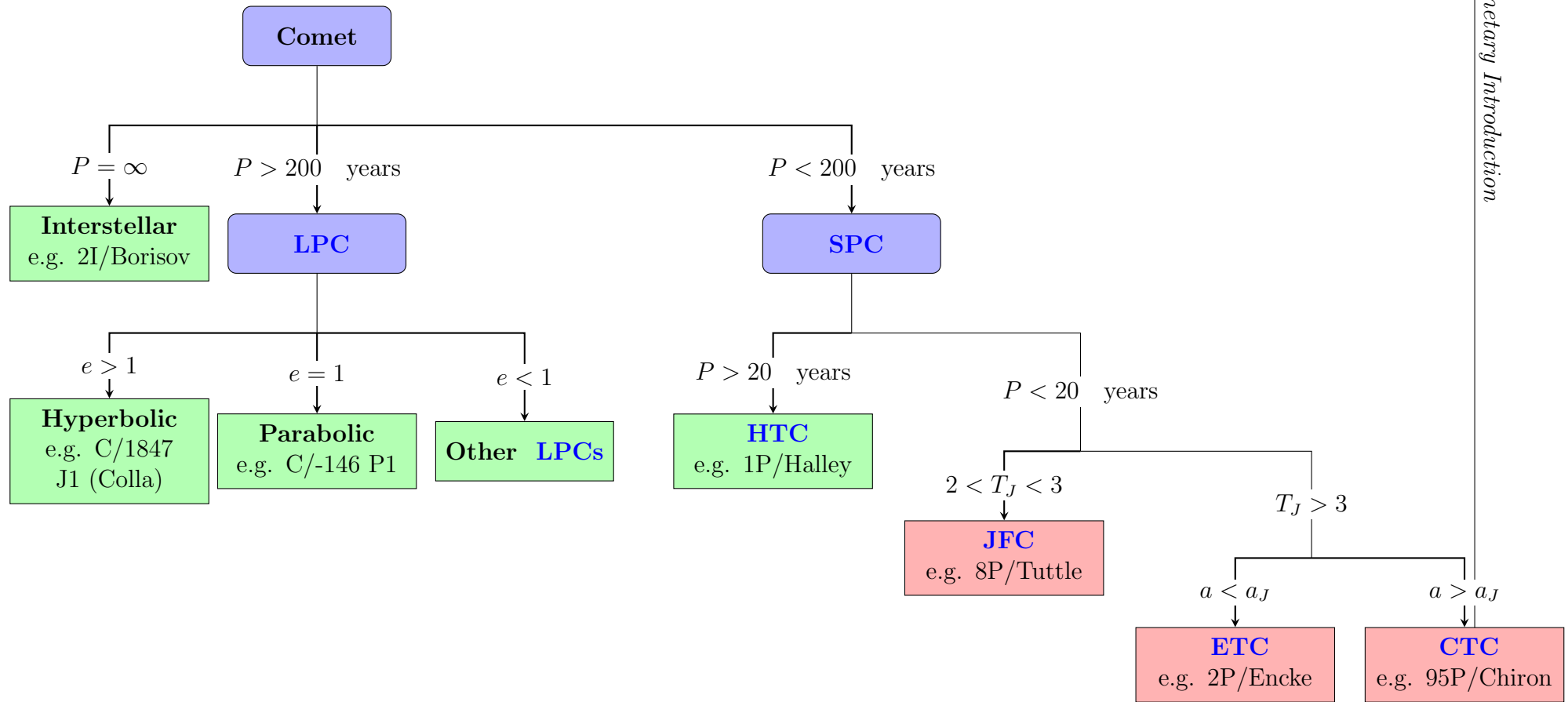


FIGURE 3.11: Flowchart displaying the classifications and criteria for different comet types as defined by [JPL](#) (*Small-Body Database Query n.d.*)

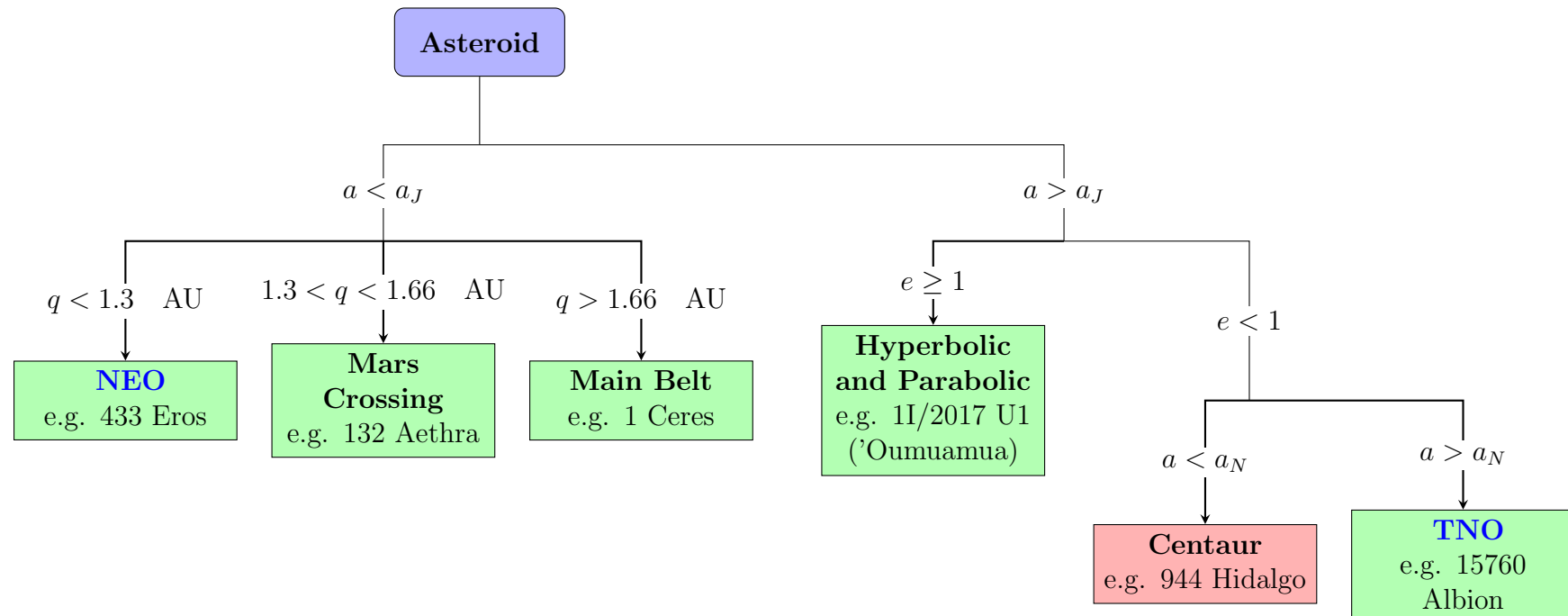


FIGURE 3.12: Flowchart displaying the classifications and criteria for different asteroid types as defined by JPL (*Small-Body Database Query* n.d.)

3.1.6.1 Long Period Comets

As seen in figure 3.11, [Long Period Comets \(LPCs\)](#) (or non-periodic comets) are usually classed as comets with orbital periods greater than 200 years (Fernández 2005; Thomas 2020). [LPCs](#) have highly eccentric orbits, resulting in near-parabolic or hyperbolic orbits, and usually have high inclination angles, as seen in figure 3.10d. The high [eccentricity](#) and vast variation in inclination angles suggest that these objects originate from the Oort cloud rather than the [EKB](#). By definition, [LPCs](#) have fewer journeys into the inner [SS](#) than [SPCs](#) and are therefore a purer sample of a comet at the point of its creation.

3.1.6.2 Short Period Comets

[Short Period Comets \(SPCs\)](#) are classified as having an orbital period less than 200 years (Fernández 2005; Thomas 2020). Due to the vast variation in orbits when minor-bodies interact regularly with the planets, most notably Jupiter, [SPCs](#) are separated further into different groups, based on their orbital periods once again. Those with periods greater than 20 years are considered to be [Halley-Type Comets \(HTCs\)](#), and those with periods less than 20 years can be further categorised. This further categorisation is based on a value known as the Tisserand parameter.

The Tisserand parameter is a value calculated to distinguish/categorise comets with respect to their orbital parameters. Derived by Tisserand (1889), this parameter was used to separate [JFCs](#) and [HTCs](#), at a boundary of $T = 2$. It is used in restricted three-body problems (in this case, the comet, Jupiter, and the Sun), ignoring other influences. The Tisserand parameter before and after an interaction with a planet remains roughly constant, despite varying during the interaction itself (Carusi and Valsecchi 1987). For a given planet, P , the Tisserand parameter, T_P is expressed as:

$$T_P = \frac{a_P}{a} + 2 \cos i \sqrt{(1 - e^2) \frac{a}{a_P}} \quad (3.1)$$

where a , i , and e are semi-major axis, inclination angle, and [eccentricity](#) of the small body, respectively, and a_P is the semi-major axis of the planet.

As seen in figure 3.11, [Jupiter Family Comets \(JFCs\)](#) are distinguished from other comets by an orbital period $P < 20$ yrs, and Jupiter Tisserand parameter $2 < T_J < 3$. Some use an objects' perihelia and aphelia distances to categorise an object as a [JFC](#), $q < q_{\text{Jupiter}}$ and $Q < q_{\text{Saturn}}$ (Sarid et al. 2019). The dynamical lifetime of [JFCs](#) can range from $3 \times 10^3 - 3 \times 10^4$ yr with a median lifetime of 1.2×10^4 yr (Levison and Duncan 1997). Their orbits rarely exceed that of Jupiter's and are heavily perturbed by the planet's gravitational force. [JFCs](#) originate from the [EKB](#), although not directly. Usually, [TNOs](#), icy planetesimals which lie beyond the orbit of Neptune (De Prá et al. 2024), incoming from the [EKB](#) become Centaurs first and subsequently evolve into [JFCs](#) due to Centaurs' unstable orbit (Guilbert-Lepoutre et al. 2023; Sarid et al. 2019; Wood and Hinse 2022) (see section 3.2.4). Sarid et al. (2019) identifies a 'gateway', specific orbital parameters in which objects can become [JFCs](#) or leave the family. This gateway is displayed in figure 3.13, comprising of low [eccentricity](#) objects with [perihelion](#) between 5 to 7 AU, and [aphelion](#) between similar distances. As it is the most significant object which lies in this region, [29P/Schwassmann-Wachmann 1 \(29P/SW1\)](#) was the topic of this paper due to its large size and near-constant activity. Activity in [JFCs](#) has been observed, although many more do not exhibit any activity, an active-inactive ratio of 1 : 3.5

[SPCs](#) have a median dynamical lifetime of 45 Myr (Levison and Duncan 1997). A lower estimation on the number of [SPCs](#) is 1.2×10^7 (Levison and Duncan 1997).

3.1.6.3 Centaurs

During [KBOs](#)' journey into the inner [SS](#), their orbits can be disturbed by influences from the giant planets. This results in an unstable and chaotic orbit with

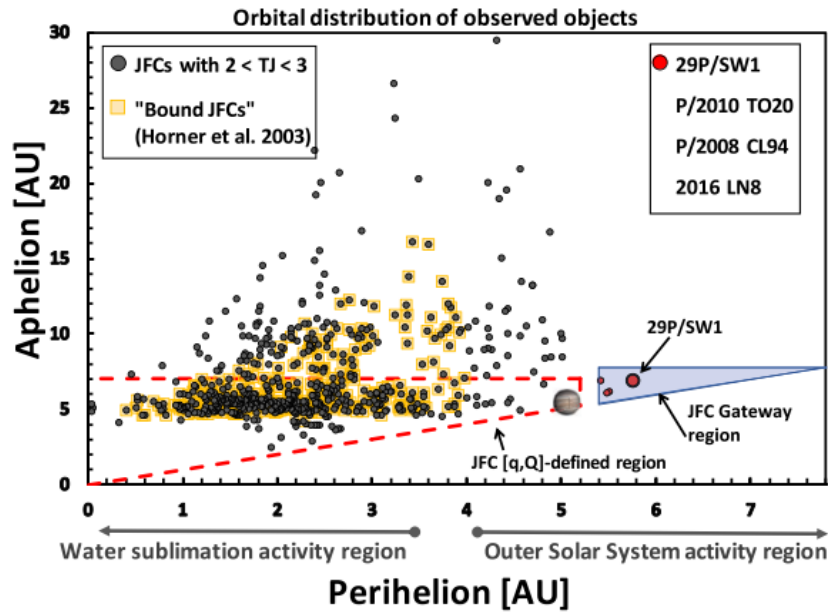


FIGURE 3.13: Distribution of JFCs with the gateway to resupply the population. Credit: Sarid et al. (2019)

perihelion ranging $\sim 12 - 30$ AU (between Jupiter and Neptune) and median dynamical lifespan of 9 Myr (Tiscareno and Malhotra 2003), although many Centaurs can have shorter perihelion distances. These objects are now known as Centaurs, transitional objects which have migrated inwards from the outer SS, first coined following the discovery of (2060) Chiron (Kowal et al. 1979). Centaur's orbital eccentricity ranges $0.2 - 0.6$.

Unlike 'normal' comets at similar heliocentric distances, Centaurs often exhibit cometary activity, even beyond Jupiter's orbit (Jewitt 2009). Regular comet activity usually begins as it crosses the frost line (the heliocentric distance at which water ice begins to sublimate, ~ 3 AU). Some objects, like 29P/Schwassmann-Wachmann 1 (see section 3.3.1.4), displays frequent and, often, violent activity, despite its orbit never crossing the frost line.

Due to the short lifespan of their orbits, Centaurs will not remain Centaurs forever. They reside in an area known as the "JFC gateway region", according to Sarid et al. (2019). Roughly a third of the Centaur population will evolve into JFCs, with two-thirds being banished to the outer SS, while a small percentage will crash into one of the giant planets (Tiscareno and Malhotra 2003). The

Centaur population is depleted by their destruction, migration into the inner [SS](#), or extradition from the [SS](#), while it is replenished by the inward migrating [TNOs](#).

More detail about the Centaur population and their activity is discussed in [sect. 3.2.4](#).

3.1.7 Comet Nomenclature

Initially in the 19th century, comets were only named after their second apparition, whilst previously, they were initially labelled with their discovery year with identifying numbers and letters after only their first apparition (IAU [2025](#)).

Early naming was based on the order that the comet was discovered despite whether the comet is periodic, P, or not, C, e.g., Halley's comet had the name P/Halley, later known as 1P/Halley as it was the first periodic comet discovered.

Newly discovered comets are designated a name depending on the date first observed and their order discovered. The designation made by the International Astronomical Union is as follows (IAU [2025](#));

- Prefix to show the type of comet, e.g., P – periodic, C – non periodic, X – unknown orbit, D – dead comet or I – interstellar minor bodies.
- Year of discovery.
- Uppercase letter identifying the half-month of discovery, e.g. A = January 1-15, B = January 16-31, and so on.
- Number representing the order of discovery within the half month.

Following this, the surname of the astronomer(s) who discovered the comet is added to the end of the name (IAU [2025](#)).

3.1.8 Photometry

Photometry is a key tool for astronomers, it is the science of measuring the light emitted or reflected from an object in space. By simply analysing the light from an object, it is possible to infer numerous parameters, such as size, rotational period, variations in colour, and detection of sudden events like outbursts.

3.1.8.1 Magnitude System

The magnitude system was devised by Hipparchus over 2000 years ago (Henden and Kaitchuck 1990). It is based on human eyesight, which does not have a linear response to changes in intensities in light. Initially, the Greeks used magnitudes of 1 to 6 to categorise over a thousand stars, with 1 being brighter than 6.

Over the years, numerous astronomers worked by using this method, including N. R. Pogson. Pogson redefined the system so that the difference between 5 magnitudes is a factor of 100 in the light flux, therefore the difference between 1 magnitude of light flux is the fifth root of 100, $\sqrt[5]{100} = 100^{(\frac{1}{5})} = 10^{(\frac{2}{5})}$.

It is therefore possible to calculate the factor of light flux between any two given magnitudes using $\left(10^{(\frac{2}{5})}\right)^{\Delta m} = \left(10^{(\frac{2}{5})}\right)^{m_2 - m_1}$, where m is the magnitude.

We can then calculate the flux of an object by comparing it with the flux of another (both with known magnitudes). The flux of an object can be calculated by comparing it with another object's flux and the magnitude of both.

$$\frac{F_1}{F_2} = \left(10^{\frac{2}{5}}\right)^{m_2 - m_1} \quad (3.2)$$

where F is the light flux.

This equation can be rearranged to calculate a magnitude,

$$m_2 - m_1 = \frac{5}{2} \log \left(\frac{F_1}{F_2} \right) \quad (3.3)$$

$$m_1 - m_2 = -2.5 \log \frac{F_1}{F_2} \quad (3.4)$$

This is known as differential photometry, using measured flux counts and a known magnitude of one of these objects resolves the other's magnitude. Due to numerous high quality sky surveys, magnitudes of stars are readily available. Measuring the magnitude of a comet, whose brightness may vary, can be found for a given image using equation 3.4. Note: the background must already be subtracted for accurate calculations.

These magnitude calculations give the magnitude of an object as viewed from Earth. Given that a minor-body's [heliocentric](#) and [geocentric](#) distances will vary constantly during its orbit, its brightness will also appear to vary. To compare measurements at different times, it is important that the magnitude is normalised, accounting for the distance from the Sun and from the observer. For stars, the absolute magnitude is calculated, this value is the magnitude of a star if it was viewed 10 parsecs from the observer. This allows consistent comparisons of different stars.

For minor-bodies, a similar technique is utilised. Calculating the magnitude of the object if it was 10 parsecs away would make the object practically invisible to any telescope made. We use the reduced magnitude, which is the magnitude of an object if it was $r_H = 1$ AU from the Sun, $\Delta = 1$ AU from the Earth, and at $\alpha = 0^\circ$ phase angle. These orbital parameters are shown in figure 3.14. This configuration of bodies is impossible (Sun and Earth would have to be in the same position), but it does give a consistent way to compare measurements.

Reduced magnitude can be calculated by,

$$R(1, 1, 0) = m - 5 \log (\Delta r_H) - \beta \alpha \quad (3.5)$$

where m is the apparent magnitude, Δ and r_H are [geocentric](#) and [heliocentric](#) distances, respectively. α is Sun-comet-Earth phase angle, and β is the linear phase coefficient.

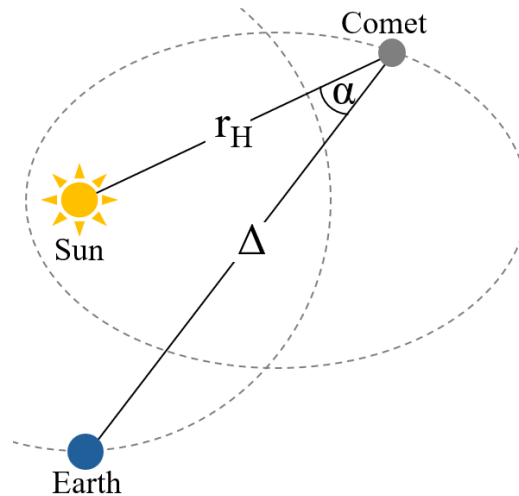


FIGURE 3.14: Diagram displaying some orbital parameters for a minor-body, r_H is the [heliocentric](#) distance, Δ is the [geocentric](#) distance, and α is the phase angle. All three parameters have influence over the apparent magnitude of an object.

3.1.8.2 Post-CCD Era

Following the advent of the [Charged-Coupled Device \(CCD\)](#), in the early 1970s, astronomical research changed forever. Historically, photomultiplier tubes were used to measure the intensity of light incident on the telescope. Photomultiplier tubes utilise the photoelectric effect to track the incoming photons. The photoelectric effect is the emission of an electron when a photon strikes a surface (Einstein 1905). Similarly, [CCDs](#) also use the photo-electric effect, although in the form of an integrated circuit.

[CCDs](#) are able to produce a 2D array containing the intensity of light (flux) for each pixel. This allows more precise photometry compared with using plates or photomultiplier readings, giving further insight into features that may appear in the image.

A commonly used analogy: imagine a bunch of buckets arranged on a surface in a square. As rain falls, the buckets begin to fill up, allowing the observer to measure how much water is in each bucket to discover the local rain fall. In this example, the [CCD](#) is the array of buckets, and the rain is the incoming light.

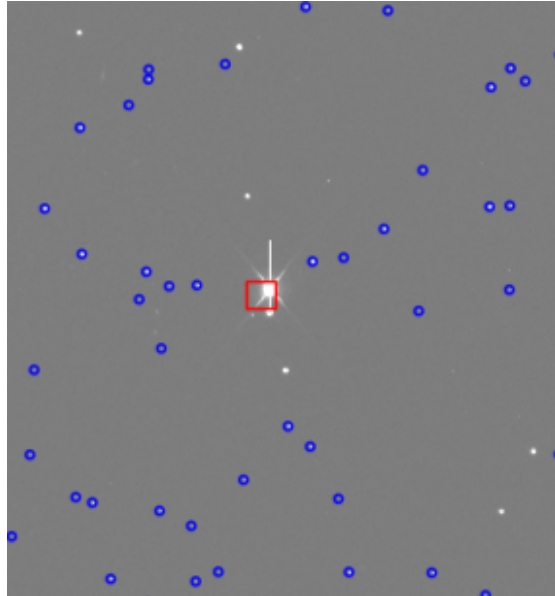


FIGURE 3.15: Example of an overexposed star. Note: overlays of circles and square have been added by the photometric pipeline used.

Naturally, [CCDs](#) can still introduce errors. A major issue is ‘spill-over’ of light into neighbouring pixels, figure 3.15. In our bucket and rain example, this would be represented as water flowing into nearby buckets when one has filled up completely. This causes bright stars to have lines protruding from it, causing major issues for the image. This can be avoided by ensuring that the image is not over-exposed.

There are two main sources of errors for [CCDs](#): readout noise and dark current.

Readout noise arises from any noise that occurs due to the instrumentation used. Major readout noise is caused when converting the incoming photons into an electrical current (Fellers and Davidson 2025). [CCD](#) manufacturers usually quote their chip’s readout noise in terms of electrons per pixel, this can be used to subtract from each pixel value.

Another source of readout noise, biases in the [CCD](#) chip can artificially change regions of the image, called the ‘flat field uncertainty’ (Howell 2006). This error is fairly easy to work around - before each series of exposures taken by the telescope, a flat field (sometimes referred to as simply ‘flats’) image is taken, i.e. an

image that should have no incoming signal. Flat fields can be in the form of taking an image with a cap on the telescope or, when this isn't possible, imaging an empty area of the sky. The counts from these flats can be subtracted from the images with data to remove any localised biases from the [CCD](#) itself.

In addition to readout noise, the dark current is an important uncertainty to take into account. This noise is due to the energy that the electrons within the circuit have if the temperature is not at 0K (Fellers and Davidson [2025](#)). Dark currents occur in all electrical systems, but are usually not an issue due to being insignificantly small. For astronomy purposes, they do become an issue. As the incoming signal is so weak, the dark current is far more significant at room temperatures (Howell [2006](#)). To rectify this as much as possible, cameras are cooled (usually with liquid nitrogen) to around -100°C , reducing the dark current to negligible amounts.

3.1.8.3 Filters

Filters restrict the wavelength of light incident on a telescope's camera, leading to detailed observations within a small wavelength range. [CCDs](#) will absorb and count all incoming photons, regardless of wavelength, therefore it is unable to discriminate the colour of the light without the use of a filter. This limited wavelength range, known as the passband, allows investigation as to how an object emits/reflects different types of light. Magnitude measurements of objects must be accompanied by the filter of the observations. Essentially, observations in different filters can detect features which may be invisible by others, see [figure 3.16](#) for an example.

The wavelengths of filters do not lie under $3000\text{ \AA}$ as the atmosphere already blocks light with shorter wavelengths (Schleicher and Farnham [2004](#)). Elements absorb and emit light differently at various wavelengths, allowing the detection of certain species if adequately narrowband filters are used (Schleicher and Farnham [2004](#)).

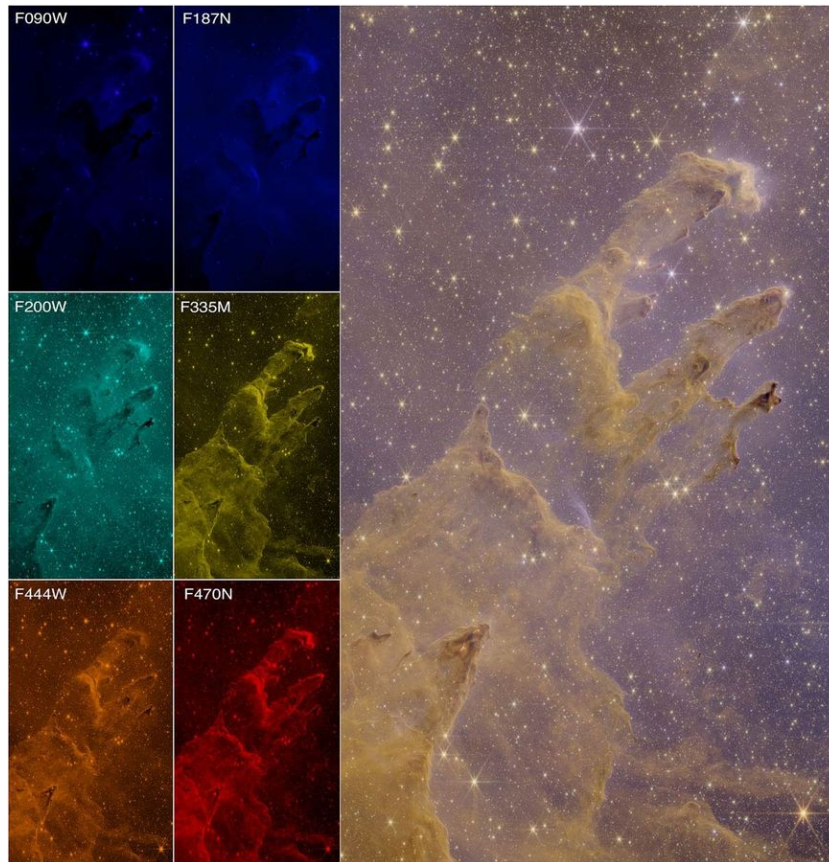


FIGURE 3.16: Images on left are single filter images obtained by [JWST](#), with the final, ‘full-colour’ composite image on the right. Credit: NASA ([2025](#)).

An important use of filters is to calculate colour indices of objects, that is, the magnitude difference of the same object in two different filters (Straižys [1995](#)), e.g. $B - V$ and $V - R$. The magnitude of the filter with a longer central wavelength is subtracted from the shorter wavelength. Broadly, this gives an indication if an object is redder or bluer, a higher value represents a redder object, while a lower value represents a bluer object. Colour indices are crucial for detailed analysis of stars, as their colour gives indications of their compositions and age (Budding [2007](#)).

Numerous photometric filter systems exist, with the Johnson-Cousins systems being traditionally the most widely used (Jordi et al. [2006](#)). The [LCO](#) network primarily uses SDSS filters, a broadband system with most filters having sharp cut-off points, rather than a more Gaussian-like shape like the Johnson

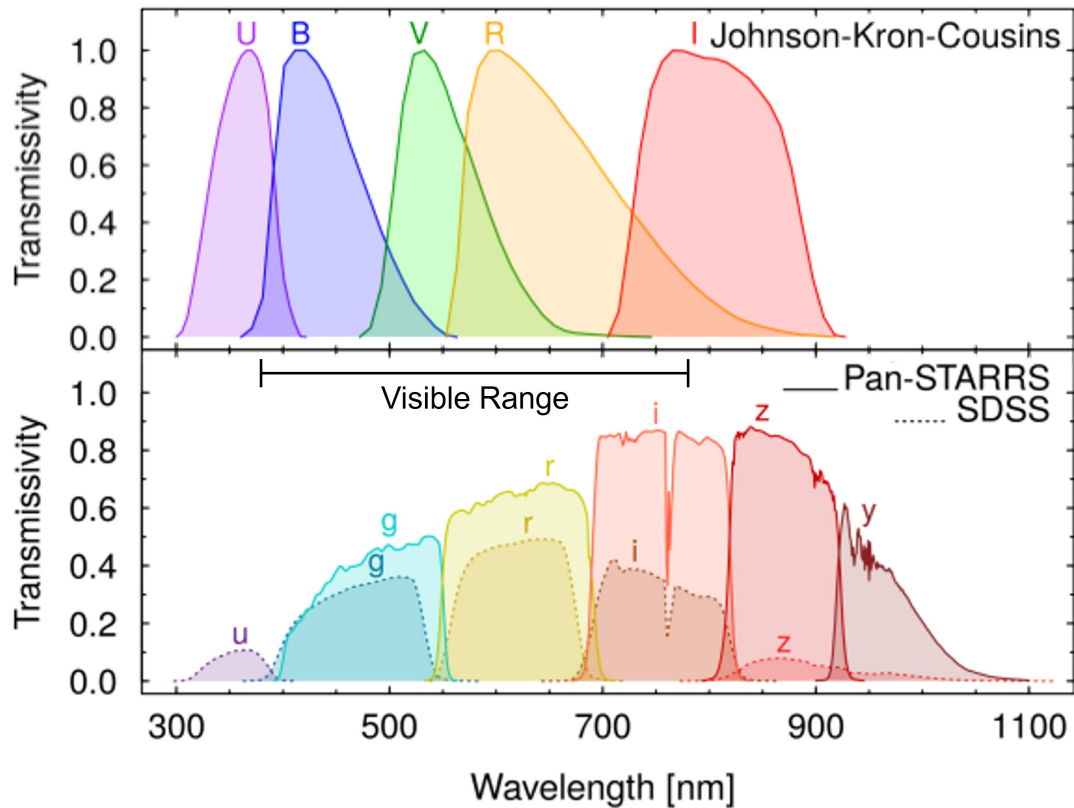


FIGURE 3.17: Transmission curves for Johnson-Kron-Cousins filter (above) and SDSS and PanSTARRS filters (below). Visible range has been added for context. Adapted from Pancino et al. (2022).

and Cousins filter systems (Fukugita et al. 1996). MuSCAT cameras are available at [Faulkes Telescope North \(FTN\)](#) and [Faulkes Telescope South \(FTS\)](#), which are able to image simultaneously in SDSS g' , r' , i' and Pan-STARRS z_s , making colour analysis convenient and easy.

For comets, using narrowband near- [IR](#) filters allows detailed observation of the dust within the coma, as contamination from gas is at its minimum, while a filter with shorter central wavelength would detect weaker emission features such as CH or NH_2 (Schleicher and Farnham 2004). For this reason, r' images of [29P/SW1](#) were prioritised, as investigating the dust emission allows clear analysis of the evolution of the coma following an outburst.

TABLE 3.1: Parameters of filters used in this study. SDSS wavelengths from Fukugita et al. (1996); all other values from Willmer (2018).

System	Filter	λ_{mean} (Å)	FWHM (Å)	$m_{\odot}$ (mag)
SDSS	u'	3540	599	-26.08
	g'	4770	1379	-26.34
	r'	6222	1382	-27.04
	i'	7632	1535	-27.38
Pan-STARRS 1	z_s	8679	1034	-27.55
Johnson	U	3618	561	-25.97
	B	4410	1004	-26.13
	V	5524	812	-26.76
Cousins	R _c	6612	1671	-27.15
	I _c	8047	1523	-27.47

3.1.9 Activity

Generally, as comets approach [perihelion](#), they begin to exhibit activity. As an observer, this event appears as a sudden brightening of the object, and often a clear expansion of the coma. Increased insolation due to a smaller heliocentric distance leads to the heating of ices within the nucleus, causing the release of gases and dusts into the coma, primarily H₂O, and reflecting more sunlight. Often, activity is increased post-[perihelion](#) compared [perihelion](#) with pre-perihelion (Mazzotta Epifani et al. 2009). Differences in the compositions of [volatile](#) gases released during activity do not vary drastically between [LPCs](#) and [SPCs](#) (Meech et al. 2009), suggesting a similar [volatile](#) composition between the two categories.

During an outburst, dust and gas is ejected from the nucleus into the coma. This can be ejected isotropically, with no distinct source, or via a discrete source, potentially like what is evident in figure 3.19, where a jet of material can be seen originating from the nucleus (Sekanina 1987). Figure 3.18 shows a jet of material having been ejected from the nucleus of [29P/SW1](#) and its subsequent development over time. This material expands, and eventually encompasses the whole nucleus (Miles et al. 2016). Material ejected at velocities lower than the escape

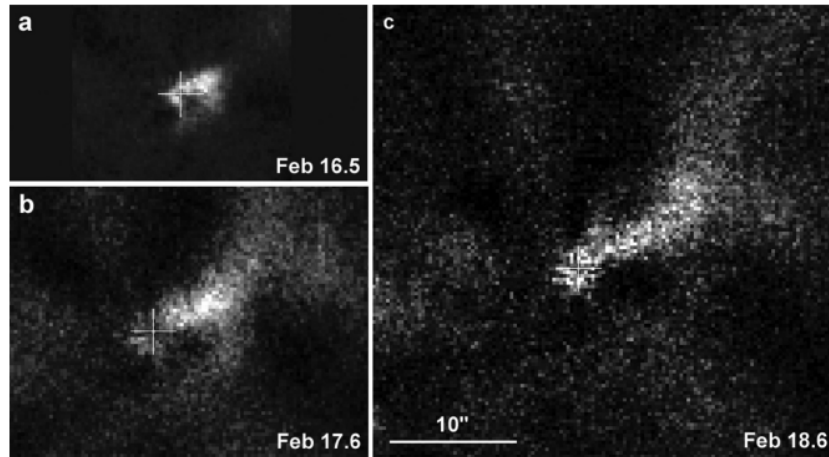


FIGURE 3.18: Development of a jet emanating from a source on the surface of [29P/SW1](#) over 2 days. Credit: Miles et al. ([2016](#)).

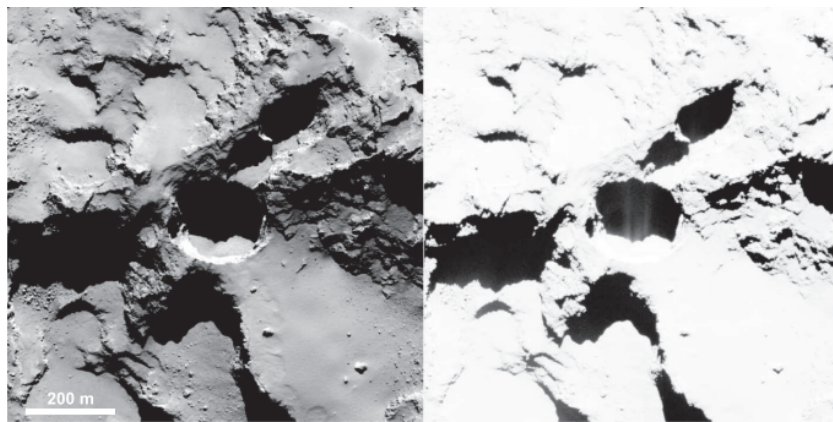


FIGURE 3.19: Image of an active pit on [67P/CG](#) by the Rosetta craft. Image on the right is with enhanced contrast, showing material being ejected from the nucleus. Credit: Sierks et al. ([2015](#)). [heliocentric](#)

velocity of the object will redeposit on the surface of the nucleus following the ‘fall-back’ period (Whipple [1980](#)).

Direct [sublimation](#) of ices is a major mechanism for outbursts, this is not always the case, as activity has been seen in objects where they do not cross the [frost line](#), yet exhibit significant activity at large [heliocentric](#) distances (Mazzotta Epifani et al. [2009](#); Meech et al. [2009](#)). While water-ice is the most common [volatile](#) within comets, there are also significant proportions of carbon monoxide (CO) and carbon dioxide (CO₂). Carbon monoxide is the most [volatile](#)

of these molecules, with [sublimation](#) temperature of 25 K, compared with temperatures for carbon dioxide and water of 72 K and 152 K, respectively (Yamamoto [1985](#)). CO and CO₂ ices could sublimate at distances beyond the [frost line](#), contributing to activity at large [heliocentric](#) distances.

Gronkowski ([2002](#)) investigates different mechanisms which could explain activity triggered by sources other than solar radiation. They discuss hydrogen cyanide (HCN) polymerisation, proposed by Rettig et al. ([1992](#)), as a mechanism to cause outbursts, or as a way to trigger the conversion of [Amorphous Water Ice](#) into [Crystalline Water Ice](#). This species has been identified in numerous comets at proportions of 0.1-0.2% relative to the water present (McKay and Roth [2021](#)). HCN polymerisation could release 10^{12} J of energy, sufficient to heat the nucleus from 100 K to ~ 150 K, this being sufficient to cause the [sublimation](#) of water (Rettig et al. [1992](#)).

Heat could be generated within the nucleus via crystallisation of [Amorphous Water Ice](#), a structure with high surface area, to a stable hexagonal structure, [Crystalline Water Ice](#), an irreversible process (Ghormley [1968](#)). This conversion releases energy and any trapped impurities within the original [AWI](#) structure, such as CO or CO₂. Comets entering the inner [SS](#) for the first time from the [EKB](#) or Oort cloud are known as ‘dynamically new’, as they have yet to experience evolutionary changes due to approaches to [perihelion](#). Activity seen in dynamically new comets is unlikely to be driven by the crystallisation of [AWI](#) (Meech et al. [2009](#)). More detailed discussion of the conversion of [AWI](#) into [CWI](#) is presented in section [3.4.1.1](#).

Activity can exhibit seasonality, with maxima and minima in activity occurring during an object’s orbit. An object’s rotational inclination angle means that the sub-solar point shifts over the year, leading to increased insolation on a certain area (Keller et al. [2017](#)). We, of course, see this occur on Earth, with the Northern hemisphere inclined towards the Sun (experiencing spring/summer) from

March to September, while the Southern hemisphere experiences winter/autumn during this period. This enhanced heating can lead to cracks in the non-volatile crust, allowing sublimated ice to escape (Weissman 1986). This has been observed for numerous comets, including 1P/Halley, 49P/Arend–Rigaux, and 67P/CG (Eisner et al. 2017; Keller et al. 2017; Weissman 1986).

While proximity to the Sun naturally affects the activity exhibited, seasonality has also been observed in objects with less elliptical orbits. Main belt comets and active asteroids have shown seasonality in their activity, despite remaining in a fairly circular orbit (Hsieh et al. 2004, 2011).

29P/SW1 exhibits regular and intense outbursts, its constant heliocentric distance of ~ 6 AU would not be sufficient for water-ice sublimation to occur due solely to insolation. Hypotheses about its outbursting mechanisms are discussed in sect. 3.4.

3.2 Centaurs

Centaurs are objects which exhibit properties of both asteroids and comets, like their mythical namesake of half human, half horse. Their orbits are chaotic due to regular interactions with the giant planets (Bailey and Malhotra 2009; Sarid et al. 2019; Tiscareno and Malhotra 2003), and have short dynamical lifespans ($< 10^7$ years) (Tiscareno and Malhotra 2003).

Their population is most likely topped-up by objects from the TNO population, following orbital changes due to perturbations from the giant planets and collisions with other TNOs (Tegler et al. 2008), although the specific class or region of space is unknown (Bauer et al. 2013; De Prá et al. 2024; Faggi et al. 2024; Fernández 1980; Jewitt 2009; Licandro et al. 2024; Tegler et al. 2008; Tiscareno and Malhotra 2003). Tsiganis et al. (2005) postulates that after the giant planets' formation and initial circular orbits, their migration outwards would have

heavily interfered with the orbits of [TNOs](#), propelling the objects into the inner [SS](#). Analysing Centaurs gives an insight into the compositions of objects in the outer regions of the protoplanetary disk (De Prá et al. [2024](#)). Investigating Centaurs can provide a better understanding of [KBOs](#) as they are more readily accessible to observe with ground-based telescopes (Guilbert-Lepoutre [2012](#)).

Historically, Centaurs were identified as either comets or asteroids, and designated as such when discovered based on whether the object exhibited activity or not, respectively (Fernández et al. [2018](#)). Following the discovery of (2060) Chiron (Kowal et al. [1979](#)), the creation of the group ‘Centaur’ was proposed to better characterise these unusual objects.

3.2.1 Characteristics

Given the transitional and varied nature of these objects, there isn’t a single definition available for a Centaur (Jewitt [2009](#)). Generally, they are objects which orbit between the orbits of Jupiter and Neptune (Licandro et al. [2024](#)).

In their study of active Centaurs, Jewitt ([2009](#)) uses the following definition:

- $a_J < q < a_N$
- $a_J < a < a_N$
- Not in a 1:1 orbital mean-motion resonance with a planet.

At larger [perihelion](#) distances, objects are more likely to have greater orbital inclinations to the ecliptic, this could allow Centaurs to avoid objects orbiting at near-zero inclination angles, allowing them to survive for long periods (Tiscareno and Malhotra [2003](#)). Lower inclinations are also associated with brighter objects, although Bauer et al. ([2013](#)) mentions that the low sample size of objects at higher inclinations may introduce a bias - although Fernández et al. ([2013](#)) discusses how objects with orbits of larger inclination angles most likely originate from comets, which appear darker.

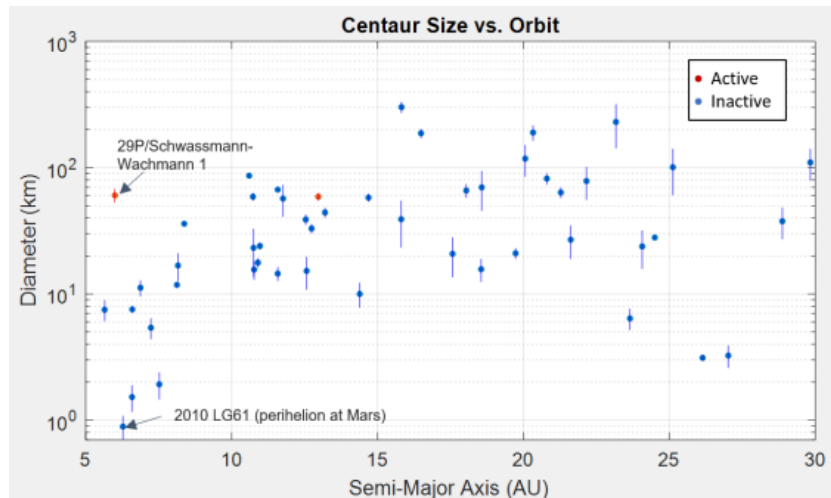


FIGURE 3.20: Distribution of Centaur nuclear diameter versus semi-major axis. [29P/SW1](#) is the largest Centaur at small semi-major axis. Credit: Vance and Thangavelautham (2023).

Optical colours of Centaurs can vary greatly, ranging from neutral to very red (Jewitt 2009). A neutral colour has been associated with higher levels of activity when (e.g. (2060) Chiron), and those that are redder suggest a less active object (e.g. (5145) Pholus) (Jewitt 2009). Numerous studies have investigated this bimodality in the colour distribution (Bauer et al. 2013; Fernández et al. 2018; Jewitt 2009; Lacerda et al. 2014; Peixinho et al. 2012; Stansberry et al. 2007; Tegler et al. 2008). Those in the ‘neutral’ group appear greyer as its $B - R$ value is similar to the Sun’s value and albedo $p_v \sim 0.15$, while the smaller ‘red’ group is $B - R > 1.4$ mag and albedo $p_v \sim 0.05$, with clustering at ~ 1.85 mag and a higher distribution of colours (Bauer et al. 2013; Lacerda et al. 2014). Objects in the ‘red’ group are likely composed of [refractory](#) organic compounds (De Prá et al. 2024), and likely formed and/or remain in the outer [SS](#) (Lacerda et al. 2014), an ancient surface inflicted by irradiation by cosmic and solar rays, while the ‘grey’ group has had its surface reworked due to impacts over time (Fernández et al. 2018; Tegler et al. 2008).

Tegler et al. (2008) suggests that there may be a correlation between an object’s $B - R$ colour index and its albedo, this was confirmed by Bauer et al. (2013). During an object’s life from [TNO](#) to Centaur to [JFC](#), its albedo changes, with [JFCs](#) appearing darker than Centaurs and its precursors in the [EKB](#), with a

mean albedo value for Centaurs $p_v = 0.08 \pm 0.04$ (Bauer et al. 2013). Albedo for the neutral group is $p_v = 0.06 \pm 0.02$, and for the red group $p_v = 0.12 \pm 0.05$ (Bauer et al. 2013; Stansberry et al. 2007). Stansberry et al. (2007) also identifies differences in albedo relating to an object's size, diameters > 1000 km have an albedo 0.60, while objects smaller than this have an albedo 0.25. Interestingly, there has been no correlation detected between albedo and size in the JFC population (Fernández et al. 2013).

3.2.2 Composition

TNOs can be characterised by their surface compositions; bowl (predominantly water and silicates), double-dip (predominantly CO₂ and CO ices), and cliff-types (predominantly carbon ices and complex organics) (Pinilla-Alonso et al. 2024). These names originate from the 3 μ m absorption shape, see figure 3.21. Differences in surface compositions are due to the incident radiation or collisions with other objects (Gil-Hutton 2002), leading to variations in the same class of object - this has a larger effect on Centaurs as they migrate inwards.

Centaur spectral-classes can deviate greatly from the TNO population, likely losing the more volatile ices due to sublimation as their heliocentric distance decreases. For smaller Centaurs, only the less-volatile ices and refractory compounds will remain (De Prá et al. 2024). CO₂ has been found to dominate comae of JFCs, suggesting that the object may have already exhausted its supply of the more volatile CO (Harrington Pinto et al. 2022). Licandro et al. (2024) found that no Centaur could be categorised as a double-dip-type and that 30% of Centaurs did not fit a spectral-class, possibly due to the loss of some ice species or solar radiation processing nucleus surface. They suggest an addition of an additional class, shallow-type, similar to bowl-types. Bowl-Centaurs are $\sim 50\%$ ice, $\sim 30\%$ amorphous silicates, and $\sim 10 - 20\%$ complex organics, while shallow-Centaurs contain no CO₂, $\sim 70 - 80\%$ amorphous silicates, $10 - 20\%$ water ice, and $\sim 7 - 8\%$ complex organics (Licandro et al. 2024).

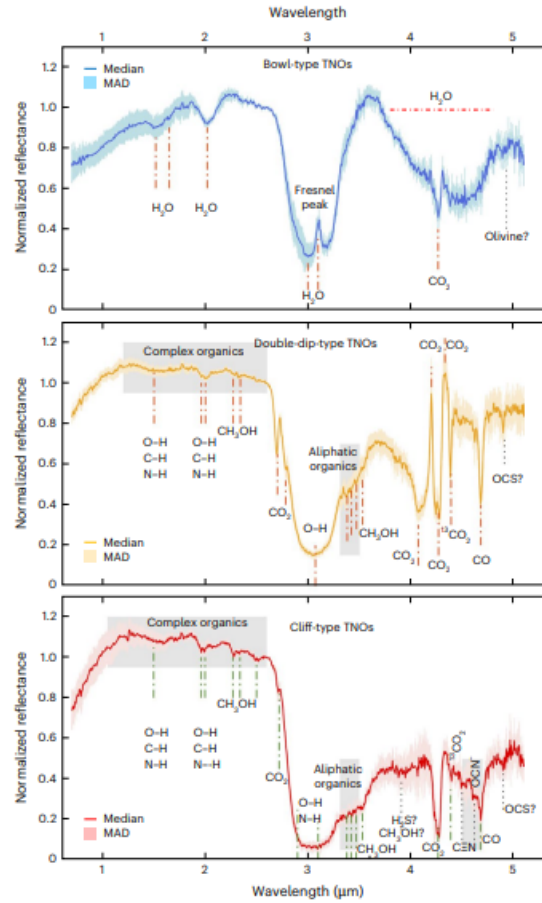


FIGURE 3.21: Spectral distribution of different types of TNO, bowl-, double-dip-, and cliff-types. Species responsible for absorption features are labelled.
Credit: Licandro et al. (2024).

Correlations for both Centaurs and TNOs between albedo with orbital distance, size, and colour have been identified by numerous studies (Peixinho et al. 2012; Santos-Sanz et al. 2012; Stansberry et al. 2007), likely due to the increased insolation due to a smaller heliocentric distance.

The density of Centaurs can vary from $0.5 - 1.7 \text{ g cm}^{-3}$ for objects with diameters less than 200 km (Vance and Thangavelautham 2023), as with ‘normal’ comets.

3.2.3 Transitional Nature

Fernández (1980) first proposed that a belt of icy bodies far from the Sun could be the reservoir for topping up the constantly dwindling comet population. TNOs

in the [EKB](#) generally have low [eccentricity](#) orbits, vastly different to most comets - only when their orbits are perturbed by other [KBOs](#) or the giant planets do they develop a highly eccentric orbit, plunging the objects into the inner [SS](#) (Levison and Duncan [1997](#)).

As Centaurs migrate inwards from the [EKB](#), the surface undergoes multiple changes. Incidental, long-term solar radiation forms complex organic molecules, this creates a crust known as the ‘irradiation mantle’ (Licandro et al. [2024](#)). This mantle can decay due to collisions with other bodies, allowing fresh, non-irradiated material to cover the surface. These procedures are mentioned by Gil-Hutton ([2002](#)) for [TNOs](#), but a Centaur’s surface can undergo further evolution due to their smaller [heliocentric](#) distances, resulting in greater intensity of incoming radiation (Licandro et al. [2024](#)).

Dynamically new comets (more pristine samples of comets, untainted by close encounters with the Sun) originating from the Oort cloud have a greater CO_2 production rate compared with that of CO at [heliocentric](#) distances $r_H > 2.5 \text{ AU}$, this is not seen during an object’s second or later visits into the inner [SS](#) where CO dominates (Harrington Pinto et al. [2022](#)). The surface composition of new objects are irreversibly changed following subsequent approaches to [perihelion](#). The greater intensity of radiation can trigger phase transitions of the ices underneath the crust developed. Outgassing of the sublimated ices can also expel dust. If this dust does not have sufficient velocity to escape the gravitational pull of the object, the material falls back onto the nucleus, forming a dust mantle (Licandro et al. [2024](#)).

Increased temperatures following the inward migration of new Centaurs to the giant planets region can trigger the [sublimation](#) of CO and CO_2 , leading to a change in the surface composition, from ice-rich to more [refractory](#) composition (Licandro et al. [2024](#)). Any superficial CO and CO_2 on an incoming [TNO](#) will likely sublime and deplete quickly as they move into the giant planet region, as prior to this, it would not be driving any activity (Licandro et al. [2024](#)).

Licandro et al. (2024) suggests that [LPCs](#) may retain more CO given they originate from further afield than the [EKB](#), leading to activity at greater distances than [TNOs](#). These objects must contain reservoirs of ice underneath their surfaces if activity occurs following their initial solar approaches.

Due to somewhat regular and intense interactions with the giant planets, their dynamical lifetime is relatively short, median 9 Myr (Jewitt 2009; Tiscareno and Malhotra 2003). Centaurs will either die or transition into a different classification of object. Centaurs which don't exhibit activity (inactive Centaurs) have dynamical lifetimes roughly twice as long as active Centaurs (1.37×10^6 yr and 2.8×10^5 yr, respectively), likely due to active Centaurs having orbits closer to Jupiter's and at lower inclinations, leading to greater opportunities for orbital perturbations (Fernández et al. 2018). Death can occur from impacting into one of the giant planets, or torn apart due to gravitational forces during encounters with the giant planets (Jewitt 2009). Two-thirds of the Centaurs which avoid this fate will be ejected into interstellar space (Tiscareno and Malhotra 2003), while the remaining third will likely become a [JFC](#) - this is how the [JFC](#) population is resupplied (Licandro et al. 2024).

There is a distinction between the object a Centaur becomes based on its activity; inactive Centaurs are more likely to produce [HTCs](#) and [LPCs](#) (with Tisserand parameters with respect to Jupiter $-2 \lesssim T_J \lesssim 3$), while active Centaurs become mainly [JFCs](#) (with Tisserand parameters with respect to Jupiter $2 \lesssim T_J \lesssim 3$), *if* they survive long enough (Fernández et al. 2018). Transitioned inactive Centaurs are expected to become active at low [perihelion](#) distances when the ices sublimate and are expelled from the nucleus, like 'regular' cometary activity (Fernández et al. 2018). Fernández (2005) attributes these differences due to the evolution of the object, rather than any compositional difference when formed.

Transition from Centaur to [JFC](#) can occur via a 'gateway', a region within orbital parameter space shown in figure 3.13 (Guilbert-Lepoutre et al. 2023; Sarid et al. 2019). This gateway is not one way, i.e. from Centaur to [JFC](#), as it is

possible for gravitational perturbations to evolve a JFC into a Centaur - 77% of objects within the JFC Gateway region will become JFCs or have already been JFCs (Sarid et al. 2019). Only $\sim 20\%$ of Centaurs which become JFCs go through this gateway region (Guilbert-Lepoutre et al. 2023; Sarid et al. 2019), suggesting it is not the only way an object can transition. Objects within this region are more likely to have been thermally processed than other Centaurs which cross Jupiter's orbit for the first time (Guilbert-Lepoutre et al. 2023). Numerous objects have been detected within this region, including 29P/SW1 - the largest and only continuously active object within this region (Sarid et al. 2019). For KBOs early in their evolution, there is a $\sim 30\%$ chance that the object will become a comet with perihelion $r_H < 2.5$ AU, the vast majority of those become JFCs (Levison and Duncan 1997).

Over half of simulated objects entering the gateway region for the first time have already been JFCs, with these objects being more thermally processed than other objects when they begin their transition into JFCs orbits (Guilbert-Lepoutre et al. 2023). Larger objects are believed to be more likely to return to the gateway region (Sarid et al. 2019). Water-driven sublimation can occur to around half of JFCs which pass through this region at distances less than 3 AU (Sarid et al. 2019).

Fernández et al. (2018) suggests that objects in orbit near Jupiter's orbit could have their activity dampened via depletion of their volatile material, completed conversion of AWI to CWI, or even a build up of dust on the surface of the object. Larger objects might resist this depletion (Fernández et al. 2018), which may be why 29P/SW1 remains highly active despite its proximity to Jupiter's orbit.

3.2.4 Active Centaurs

Numerous Centaurs exhibit comet-like activity at distances greater than Jupiter, too far for the activity to be driven by water-ice sublimation, which occurs in

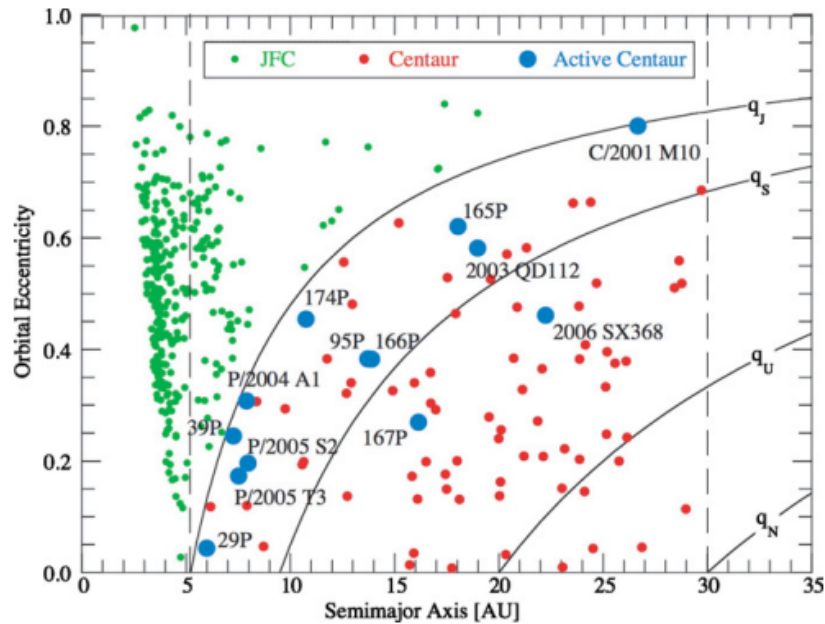


FIGURE 3.22: Orbital [eccentricity](#) of minor bodies versus semi-major axis. Different types of objects are labelled. Credit: Jewitt ([2009](#)).

regular comets within the [frost line](#) (Jewitt [2009](#)).

Carbon monoxide and carbon dioxide have been observed via spectroscopy in the Centaur population, which are far more [volatile](#) molecules than water. This high volatility is also an issue, as if this was driving the activity seen, then inactive Centaurs at distances further than Saturn would also be active, which is not seen (see figure [3.22](#)) (Jewitt [2009](#)). CO is so [volatile](#) that it would not survive the prolonged and consistent activity seen in Centaurs if it were solely driving the activity (Jewitt [2009](#)).

Measurements of the colour indices of the nuclei of active Centaurs are difficult to make due to the persistent coma surrounding them, although some measurements made are near-solar colours (Tegler et al. [2008](#)). Bimodality in colour distribution is not detected in active Centaurs compared with inactive Centaurs (Tegler et al. [2008](#)), with active Centaurs grouping near one of these groups, see figure [3.23](#).

Compared with inactive Centaurs, active Centaurs are more likely to collide with Jupiter, due to their lower orbital inclination and a nearer orbit to Jupiter

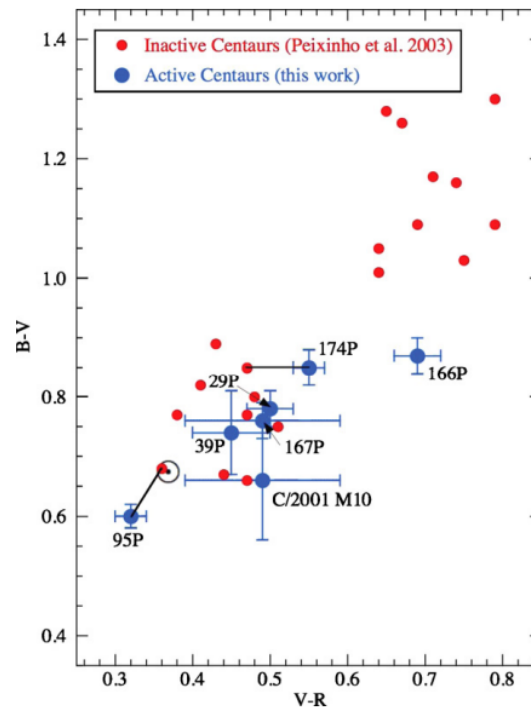


FIGURE 3.23: Colour-colour diagram of Centaurs. Active Centaurs are distinguished from inactive Centaurs. Credit: Jewitt (2009).

(Fernández et al. 2018) - collisions into Saturn are similar for both active and inactive Centaurs.

An active Centaur of note is P/2019 LD2 (ATLAS), a Centaur with a small nucleus which exhibits activity at distances further than the [frost line](#) (Borysenko et al. 2022). Within the next 40 years, this Centaur will transition into a [JFC](#) (Kareta et al. 2021). This will allow astronomers to observe in detail how Centaurs transition into different objects.

3.3 Overview of 29P/Schwassmann-Wachmann

1

First discovered in November 1927 by Arnold Schwassmann and Arno Arthur Wachmann at the Hamburg-Bergedorf Observatory, Germany, [29P/Schwassmann-Wachmann 1](#) (29P/SW1) has become famous due to its frequent and violent outbursts (Berman and Whipple 1928). It was the first discovered Centaur,

with its orbit lying entirely outside of Jupiter’s, but initially designated as a comet. Since more minor objects have been discovered with orbits further than Jupiter’s, it was reclassified as a Centaur (Kareta et al. 2025; Sarid et al. 2019; Whipple 1980), following the discovery of (2060) Chiron. 29P/SW1 is the second most active body in the SS, after Jupiter’s moon, Io (Lin 2023), due to its near constant activity. Its orbit is perturbed significantly on short timescales (Sarid et al. 2019), and is expected to move from its current orbit in 2038 (Faggi et al. 2024).

Its activity is what makes 29P/SW1 such an unusual object, undergoing > 3 major outbursts ($\Delta m \sim 1.5 - 5$) a year and many more minor outbursts (Lin 2023).

29P/SW1’s orbit is different from ‘normal’ Centaurs as its orbit is very circular, eccentricity $e = 0.04$, outside of Jupiter’s orbit, see Figure 3.24. This low eccentricity results in perihelion and aphelion distances that do not cross the frost line ($r_H \sim 3$ AU). This is the point at which water-ice begins to sublimate. Usually, this is the point where comets’ activity begins, as the ices within the nucleus sublimate and escape the crust via vents. The activity seen in 29P/SW1 therefore does not occur with the same mechanisms.

Parameter	Value
Semi-major axis	6.05 AU
Perihelion	5.78 AU
Aphelion	6.32 AU
Orbital period	14.87 yrs
Eccentricity	0.04
Inclination	9.36°

TABLE 3.2: Orbital parameters of 29P/SW1 calculated on 2023-01-01.
Credit: Giorgini and Yeomans (1999).

Its low inclination and low eccentricity places the object on the inner edge of the JFC Gateway Region, see figure 3.13, while its Tisserand parameter with respect to Jupiter ($T_J = 2.985$) places it on the distinction between TNOs and JFCs (Sarid et al. 2019). 29P/SW1 is likely to be a recent new arrival in

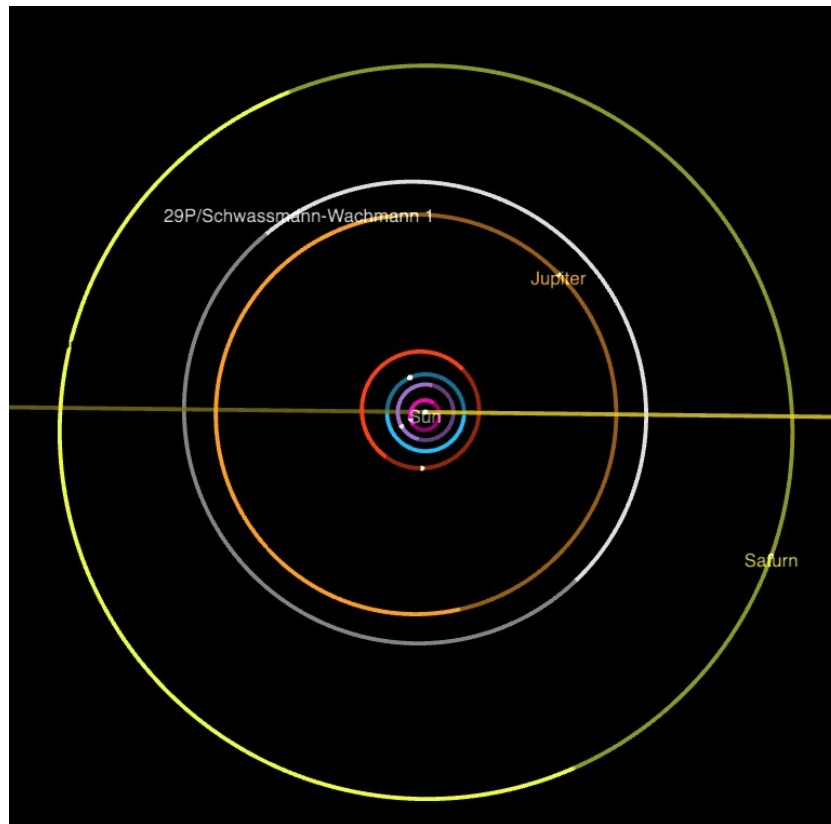


FIGURE 3.24: Diagram showing [29P/SW1](#)'s orbit from above relative to the other planets in the [SS](#). Credit: Gill et al. ([2025](#)).

the gateway region instead of a returning visitor as interactions with the giant planets would be very prominent given its low inclination. (Sarid et al. [2019](#)). This is supported by the Centaur's activity level, which is similar to the dynamically new [LPCs](#) at similar [heliocentric](#) distances (Sarid et al. [2019](#)). Guilbert-Lepoutre et al. ([2023](#)) estimated that [29P/SW1](#) has greater than 50% chance of being previously thermally processed suggesting that the surface composition of the object has already been altered physically and chemically, and thus not representative of the object's initial state.

Simulations of [29P/SW1](#)'s historical and future orbit have been conducted to investigate how long it has been in its current orbit and what will happen to it over time. Sarid et al. ([2019](#)) calculated that its orbit can be traced back roughly 700 years, where the simulations begin to diverge due to chaotic and strong interactions with Jupiter, backtracking its orbit matches with its orbit measured almost 100 years ago when it was first discovered. Their simulations

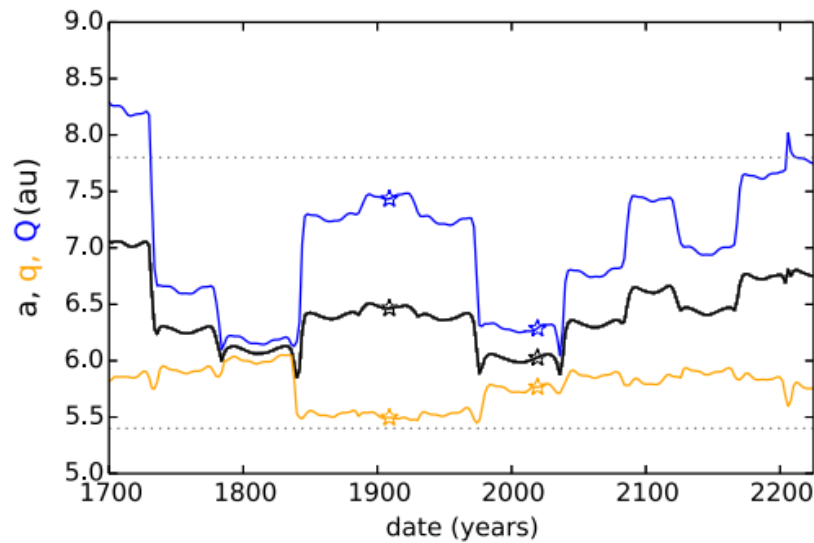


FIGURE 3.25: Simulated changes in orbital parameters from 1700 to 2200.
Credit: Sarid et al. (2019).

theorise that in the next 10,000 years, it has $\sim 65\%$ chance of transitioning into a JFC. Figure 3.25 shows the simulated changes in its orbit, and a lower estimation on how long it has remained in this orbit. If the Centaur transitioned into a comet, it would be the largest SPC discovered, and likely the brightest comet. It was believed to be rare for a Centaur to transition to a JFC on the timescale of human civilisations (Lisse et al. 2022; Sarid et al. 2019), though the discovery and orbital changes of P/2019 LD2 (ATLAS) challenges this (Kareta et al. 2021).

3.3.1 Physical Characteristics

Despite being one of the most observed comets ever, there is little certainty in the specific characteristics of 29P/SW1. Numerous studies result in, sometimes, greatly varying values for different parameters. This is mainly due to the difficulty in observing the object, and its highly active nature causing great difficulty in having an extended period of quiescence to observe the nucleus exclusively.

3.3.1.1 Rotational Period

Numerous attempts at unlocking the rotational period of nucleus of [29P/SW1](#) have been made, most using different methods.

Outbursts have been assumed to be directly linked to [29P/SW1](#)'s rotational period, with insolation triggering an event to occur. This is logical as all proposed mechanisms requires an initial heat source to increase the sub-surface pressure.

Stellingwerf ([1978](#)) first proposed a method to derive the period of Cepheid variable stars, known as [Phase Dispersion Minimisation \(PDM\)](#). This technique folds data into bins, using trial periods, with the aim to reduce the overall variance to a combined bin variance ratio. Values near 1 show that a real period was not found, while a local minima suggests a period. This method does show harmonic periods and, as Meech et al. ([1993](#)) notes, could indicate a rotation not about a single axis. Whole data sets or only outbursts dates have been used in conjunction with this method to estimate a rotational period of [29P/SW1](#). Similarly, the Lomb-Scargle periodogram is an algorithm to deduce a periodic signal in irregularly sampled data (VanderPlas [2018](#)). It is crucial that both these methods are primarily for irregular sampled data, such is the case of astronomical observations.

Jet features in the coma can be seen in observations, and highlighted using a Larson-Sekanina filter. A Larson-Sekanina filter, also called a 'rotational gradient filter' highlights non-circular features within an object's coma by stacking two identical images rotated (Larson and Sekanina [1984](#)). Assessing the development of a jet and its curvature could give an indication of the rotational period, especially if this material was not strongly gravitationally bound to the nucleus. Stansberry et al. ([2004](#)) gives a formula to calculate this period,

$$P \simeq \frac{2\pi \left(\frac{\Delta r_{jet}}{\Delta \theta_{jet}} \right)}{v_{jet}} \quad (3.6)$$

where Δr_{jet} , $\Delta\theta_{jet}$, and v_{jet} are the distance of the end of the jet from the nucleus, change in direction of the jet relative to the source, and the velocity of the jet, respectively. Schambeau et al. (2021) proposes that the curvature seen in the outburst material is due to the solar radiation pressure forming a small dust tail, rather than due to the nucleus' rotation.

Miles (2016a) notes that any changes in rotational period due to the energy released during an outburst is minimal, with a mass loss rate of $\sim 3 \times 10^{-7} \text{ \% yr}^{-1}$ of the object's total mass.

TABLE 3.3: Published estimates of the nuclear rotational period of [29P/SW1](#), ordered by publication date. Observing intervals and the methods used to derive each estimate are also listed.

Source	Rotational period (d)	Observing interval	Method
Whipple (1980)	5.0 ± 0.08	1927–1977	Outburst periodicity
Meech et al. (1993)	$0.59, 1.35^a$	August 1987	PDM
Stansberry et al. (2004)	≥ 60	November 2003	Jet curvature
Ivanova et al. (2012)	12.1 ± 1.2	December 2008	Jet curvature
Ivanova et al. (2012)	11.7 ± 1.5	February 2009	Jet curvature
Miles (2014)	$57.2/n \pm 8\%^b$	2010–2012	Outburst PDM
Perna et al. (2015)	0.96 ± 0.56	2007	Jet curvature
Miles (2016a)	57.71 ± 0.06	2002–2014	Outburst PDM
Stoddard-Jones (2021)	57.5	2010–2014	Outburst PDM
Shubina et al. (2023)	57 ± 2	2012–2019	Jet curvature
Betzler (2023a)	0.97	2015–2022	Lomb–Scargle periodogram

^a Complex spin state reported; both principal periods are listed.

^b Where $n = 1, 2, 3$

4 sources found a rotational period ~ 57 d, utilising different methods. This would be the longest confirmed rotational period of any TNO, Centaur, or comet - with the longest rotational period included by JPL (2025) being 12.5 d. It is important to note that Miles (2016a) nor Stoddard-Jones (2021) did not find any periodicity outside of the observing interval mentioned.

3.3.1.2 Albedo

Albedo is the ratio of how much light is reflected with respect to the incident light. It is a value between 0 and 1, with 0 representing an object which absorbs all light incident, and 1 reflecting all light. Numerous factors contribute towards an object's albedo, and is discussed in sect. 2.4.1.3.

Morrison (1973) presents an expression which calculates an object's albedo based on visual and IR magnitudes.

$$V - m_\lambda = \text{const.} - 2.5 \log(A) + 2.5 \log(B_\lambda (\bar{T}(1 - A)^{1/4})) \quad (3.7)$$

Hartmann et al. (1982) also uses colour to estimate the albedo, via calculating an α -index (position of an object on a colour-colour diagram). This is directly proportional to the albedo and ice-to-dust ratio.

The Standard Thermal Model has been utilised by some researchers (Lebofsky and Spencer 1989), which is defined as,

$$\pi R_N^2 (1 - A) S = \eta \epsilon \sigma_{SB} R_N^2 \int_{-\pi}^{\pi} \int_{-\pi/2}^{\pi/2} T^4(\theta, \phi) \cos \phi \, d\phi \, d\theta \quad (3.8)$$

where A is bolometric Bond albedo, S is solar flux at an object's heliocentric distance, η is normalisation constant to find the flux at zero phase angle, ϵ is wavelength-independent emissivity, σ_{SB} is Stefan-Boltzmann constant, and $T(\theta, \phi)$ is model temperature, given by,

$$T(\theta, \phi) = T_{SS} \cos^{1/4} \theta \cos^{1/4} \phi \quad (3.9)$$

for $\theta < \pi/2$. The sub-solar temperature T_{SS} is defined as,

$$T_{SS} = \left[\frac{(1 - A)S}{\eta \epsilon \sigma_{SB}} \right] \quad (3.10)$$

where θ and ϕ are a given latitude and longitude location.

Harris (1998) built on the standard thermal model and gives a derivation of the radius and nucleus simply using the absolute magnitude of an object.

$$p_v = \left(\frac{1329}{D} \right)^2 \cdot 10^{-0.4H_v} \quad (3.11)$$

where p_v is visual geometric albedo, D is nuclear diameter, and H_v is absolute visual magnitude of an object. Stansberry et al. (2004) notes that this is the method adopted by the IAU to derive an object's albedo.

Both eq. 3.8 and 3.14 require thermal modelling of the nucleus to derive the albedo and nuclear radius.

For a detailed investigation of the nuclear albedo, it is required to remove the coma contributions to find the true nuclear flux for a given observation. Stansberry et al. (2004) uses a fitted power-law for the coma brightness profile, and extrapolated this towards the nuclear position to find the contribution here.

TABLE 3.4: Summary of published albedo values of 29P/SW1. Comet and Centaur average are listed for context.

Source	Albedo	Method
Cruikshank and Brown (1983)	0.13 ± 0.04^a	Eq. 3.7
Stansberry et al. (2004)	0.025 ± 0.01^a	Eq. 3.11
Stansberry et al. (2007)	$0.046^{+0.052a}_{-0.019}$	Eq. 3.11
Bauer et al. (2013)	0.033 ± 0.015^a	Eq. 3.11
Perna et al. (2015)	0.023 ± 0.003^a	Eq. 3.8
Schambeau et al. (2015)	0.31^b	Eq. 3.11
Jewitt (1991)	0.07 ± 0.05	Comet Average
Fernández et al. (2013)	0.04 ± 0.02	JFC Average
Duffard et al. (2014)	0.069 ± 0.048	Centaur Average

^a Geometric visual albedo

^b Geometric albedo for $\lambda = 5.8 \mu\text{m}$

No correlation has been found between an object's orbital parameters and its albedo (Duffard et al. 2014). Estimations for 29P/SW1's albedo have mostly been darker than those for all comet and Centaur averages. Geometric visual albedo estimations were all ≤ 0.13 , with most under 0.05 with the exception of the oldest measurement by Cruikshank and Brown (1983). It is clear that 29P/SW1 is a very dark object.

3.3.1.3 Size

Calculating the dimensions of a minor body can be achieved in numerous ways, primarily rotational lightcurve analysis for objects with no/low activity. Unfortunately, this is very difficult to apply to 29P/SW1 given its near-constant activity. Estimations using nuclear magnitude are possible, with numerous different methods being utilised.

For asteroid size estimations, Brown et al. (1982) calculates the radius, R_N ,

$$R_N = \Delta \cdot 10^{\frac{-m_\lambda}{5}} \left(\frac{\bar{K}_\lambda}{C_\lambda} \right)^{\frac{1}{2}} \quad (3.12)$$

where Δ is geocentric distance, m_λ is apparent magnitude for a given wavelength, $\bar{K}_\lambda$ is mean zero-point flux for a given wavelength, and C_λ is a constant for a given object. This method assumes a slowly rotating, spherical, airless body in thermal equilibrium - unlikely for a comet.

Keller (1990) presents a method to calculate an object's nuclear radius,

$$\log(R_N) = 2.14 - 0.2V(1, 1, 0) - 0.5 \log(p_v) \quad (3.13)$$

where $V(1, 1, 0)$ and p_v are the reduced visual magnitude and geometric albedo, respectively.

Radius estimation can be found using the Standard Thermal Model by Lebofsky and Spencer (1989). This is discussed in the previous section (sec. 3.3.1.2).

Harris (1998) provides a simpler approximation of object size,

$$R_N = \frac{1}{2} \frac{1329 \cdot 10^{-H/5}}{\sqrt{p_v}} \quad (3.14)$$

where H is absolute visual magnitude, and p_v is visual albedo.

Kokhirova et al. (2020) provides an adaption of a method first given by Russell (1916),

$$AR_N^2 = 2.238 \times 10^{22} \cdot 10^{0.4(m_{\lambda,\odot} - m_{\lambda}(1,1,0))} \quad (3.15)$$

where A is albedo, $m_{\odot}$ is solar magnitude in a given filter, and $m_{\lambda}(1,1,0)$ is reduced magnitude in a given filter.

Meech et al. (1993) estimates the nuclear size by creating rotational lightcurves using small aperture sizes to observe the variation in brightness over time. This is used to find the ratio between major and minor axes lengths, by assessing the change in magnitude that occurs each rotation. This could then be used to estimate the average nucleus size.

Finally, a method which does not use the albedo to estimate the size, presented by Hughes (1988),

$$\log(R_H) = 1.842 - 0.2H \quad (3.16)$$

where H is the absolute magnitude.

To accommodate the fairly persistent coma seen around 29P/SW1, modelling of the coma was often conducted to find the brightness contributions of the nucleus only.

Literature values of 29P/SW1's radius are displayed in table 3.5, along with corresponding albedos used in calculations, and the method used to calculate the size. Note: values and errors were halved if diameter is presented in the publications. These values have been rounded to, at most, 1 decimal places for clarity.

TABLE 3.5: Summary of published nucleus radius estimates for Centaur [29P/SW1](#) since 1955. Albedo values and methods used are listed for each source.

Source	Albedo	Radius (km)	Observatory	Filter/Wavelength	Method
Whitney (1955) ^a	0.10	70 ± 30	–	Visual	Unknown
Roemer (1966) ^a	0.02	38.0	–	Visual	Unknown
Roemer (1966) ^a	0.70	6.4	–	Visual	Unknown
Cruikshank and Brown (1983)	0.13	40 ± 5	NASA IRTF ^b	20 μm	Eq. 3.12
Meech et al. (1993)	0.04	8.6 ± 0.1	UH 2.2m ^b	Mould R	Rotational lightcurve
Meech et al. (1993)	0.13	15.4 ± 0.2	UH 2.2m ^b	Mould R	Rotational lightcurve
Stansberry et al. (2004)	0.025	27 ± 5	Spitzer ^c	3.6–160 μm	Eq. 3.8
Stansberry et al. (2007)	0.04	$18.7^{+5.9}_{-5.7}$	Spitzer ^c	24, 70 μm	Eq. 3.8
Bauer et al. (2013)	0.033	23 ± 6.5	WISE ^c	12, 22 μm	Eq. 3.14
Perna et al. (2015)	0.023	28.2 ± 1.9	AKARI ^c	15, 24 μm	Eq. 3.8
Schambeau et al. (2015)	0.31	$30.2^{+3.7}_{-2.9}$	Spitzer ^c	5.8–70 μm	Eq. 3.13
Kokhirova et al. (2020)	0.033	44.5 ± 1.2	IAOS ^b	Johnson–Cousins BVRI	Eq. 3.15
Kokhirova et al. (2020)	0.13	22.3 ± 0.6	IAOS ^b	Johnson–Cousins BVRI	Eq. 3.15
Schambeau et al. (2021)	0.04	30.3 ± 3.1	Spitzer ^c	16, 24, 70 μm	Eq. 3.13
Stoddard-Jones (2021)	–	9.8	LCO ^b	SDSS r'	Eq. 3.16
Bockelée-Morvan et al. (2022)	0.044	31 ± 3	Herschel ^c	70–538 μm	Coma removal + Eq. 3.13

^a Values taken from Stoddard-Jones ([2021](#)) as the original publications are no longer accessible.

^b Ground-based telescope

^c Space-based telescope

Albedo has a major effect on the size estimates made, with a higher albedo leading to a smaller radius. Estimations by Meech et al. (1993) using a rotational lightcurve yielded far lower results than measurements using thermal IR observations. Numerous issues exist with the size estimate by Stoddard-Jones (2021), such as the equation used not especially appropriate to use for comets, especially for an object with a persistent coma.

3.3.1.4 Colour

Analysing the colour of the nucleus of 29P/SW1 is a difficult task given the object's near constant activity and persistent coma obscuring the nucleus (Lin 2023). 29P/SW1 appears redder than the Sun and is fairly constant with respect to an aperture, although at larger radii, the object appears bluer (Jewitt 2009).

Kiselev and Chernova (1979) notes that the colour varies based on the current level of activity due to the scattering of light based on large particles expelled during an outburst. While colour index changes can occur during outbursts, they are not always seen, Lin (2023) notes a colour change in some outbursts analysed - this is a minor change and is not the case for most outbursts. Before and after a major outbursting event, the Centaur appears slightly bluer, but this is likely due to variations in the grain size of dust in the coma, scattering the light differently (Lin 2023). Changes observed in the object's colour, especially during an outburst, gives an insight into how the distribution of different types/sizes of grain changes over time (Meech et al. 2009).

3.6

The mean values from literature for B–V, V–R, and R–I are 0.77, 0.54, and 0.53, respectively. A mean B–R value can be estimated using these means, 1.30. As discussed in sect. 3.2.1, there are two distinct colour groups for Centaurs, Tegler et al. (2008) shows these as $B - R = 1.0 - 1.4$ and $1.7 - 2.1$ mag. 29P/SW1 belongs to the grey group, with a smaller B–R. Larger Centaurs have

been found to be grey, while smaller Centaurs can be either grey or red (Duffard et al. 2014).

3.4 29P/Schwassmann-Wachmann 1 Activity

29P/SW1 outbursts on average between 3.8 – 7.3 times per year (Betzler 2023a; Trigo-Rodríguez et al. 2008a,b). These outbursts can range from $\Delta m = 1 - 5$ mag in amplitude (Miles 2016a; Trigo-Rodríguez et al. 2008b), with a median outburst duration of 3.5 hours, but can vary from 2.8 mins to 1.4 days (Betzler 2023a). Outbursts have a median peak reduced magnitude of $\Delta M = -3.0$, with range $-1.7 \leq \Delta M \leq -5.4$ mag (Betzler 2023a).

Miles (2016a) found that outbursts decreases in magnitude rate of 1.3 mag hr^{-1} . Following an outburst, the magnitude of the Centaur increases by ~ 0.15 to $7.60 \text{ mag day}^{-1}$ (Betzler 2023a; Lin 2023), taking 3-4 days to return to its normal brightness (Trigo-Rodríguez et al. 2008b).

During outbursts, shell and jet structures are visible, with the coma developing into a homogenous sphere structure over time (Lin 2023; Meech et al. 1993; Miles and Faillace 2011; Stansberry et al. 2004; Whipple 1980). Three types of emission can occur from 29P/SW1's nucleus: dust and gas, dust-only, and gas-only (Lisse et al. 2022).

Whipple (1980) measured the rotational axis's inclination angle to be 65° relative to the orbital plane. No other estimation of its rotational inclination angle have been found.

It is believed to be the only icy body which has a predictable major outburst pattern, which could be typical of the early evolution of an object transitioning into a JFC (Sarid et al. 2019).

3.4.1 Proposed Mechanisms

Given that 29P/SW1's orbit does not cross the frost line, its activity cannot be driven by water-ice sublimation (Trigo-Rodríguez et al. 2008b), i.e. 'regular' cometary activity. Activity at distances similar to 29P/SW1's orbit is not unheard of, but it is unusual for such regular outbursts to occur. Donn and Urey (1956) predicted that comet outbursts were triggered by solar heating of a volatile species of ice, suggesting that this reaction could cause particles being ejected into the coma at high velocities.

Whipple (1980) suggests that the Centaur cannot form an insulating crust on the surface of the nucleus due to the near-constant activity, further adding that within the nucleus there must be highly volatile materials or that an exothermic reaction is driving the outbursts.

Sublimation of species more volatile than water can occur at great heliocentric distances. Given the presence of CO and CO₂ in 29P/SW1, these ices could trigger, and drive, outbursts. CO sublimation, for example, could occur as deep as 10 m beneath the Centaur's surface (Enzian et al. 1997).

3.4.1.1 Crystallisation of Amorphous Ice

Due to the Centaur's large nuclear size, it has been proposed that the continuous activity could be due to the conversion of AWI into CWI (Gronkowski 2014; Jewitt 1990; Lisse et al. 2022), first proposed by Froeschle et al. (1983). Following formation in the outer edges of the SS, ices were formed by condensing from vapour at low temperatures and over a long period (Smoluchowski 1981).

When heated, amorphous ice converts into a cubic form at ~ 150 K, then rapidly crystallises into a stable hexagonal structure due to the heating of surrounding molecules from the conversion, this reaction is exothermic in pure water-ice (Ghormley 1968; Lisse et al. 2022; Prialnik and Bar-Nun 1987; Smoluchowski

1981; Venkatesh et al. 1974). Dust or gas trapped in the amorphous structure would be released following its conversion. This phase change occurs at heliocentric distances of $r_H = 5.6 - 11.1$ AU, all of 29P/SW1's orbit lies within this range, therefore sufficient temperature to trigger the crystallisation of amorphous ice (Meech et al. 2009).

The crystallisation of AWI is temperature driven and therefore the rate will vary across the nucleus's surface, with a higher rate (usually) nearer the equator and most at the sub-solar point (Guilbert-Lepoutre 2012). The energy released due to crystallisation could reach $\Delta E = 9 \times 10^4 \text{ J kg}^{-1}$ (Jewitt 1990), with this heat flowing both towards the surface and towards the nuclear core (Trigo-Rodríguez et al. 2008b). This heating could trigger the crystalline conversion elsewhere in the nucleus, or even allow sublimation of ices to occur.

This difference in crystallisation rate would allow AWI to be preserved in the poles at distances as close as $r_H = 6$ AU, although at greater rotational axis inclination angles, the rate of crystallisation would be higher (Guilbert-Lepoutre 2012). 29P/SW1 is therefore in the Goldilocks zone for the preservation of near-surface AWI, any closer and heat from the Sun would penetrate deeper into the nucleus, converting it into CWI, while further away would neither have sufficient temperature to trigger this conversion nor allow the ices to sublimate (Jewitt 1990).

Two primary methods can drive the expulsion of dust into the coma: surface rearrangements, and release of dusts and gases trapped within ices. As AWI converts into CWI, the change in density of the ice can cause surface rearrangements, such as cave-ins, landslides, or sinkholes, allowing trapped CO gas and small grains to be released (Lisse et al. 2022; Whipple 1980). Changes in the structure of the ice can cause weakening in the surface, leading to fractures on the surface (Gronkowski 2002; Trigo-Rodríguez et al. 2008b). Erosion to the surface would be required to uncover deposits of AWI beneath the crust, continuing to drive the observed activity (Enzian et al. 1997; Gronkowski 2002). A

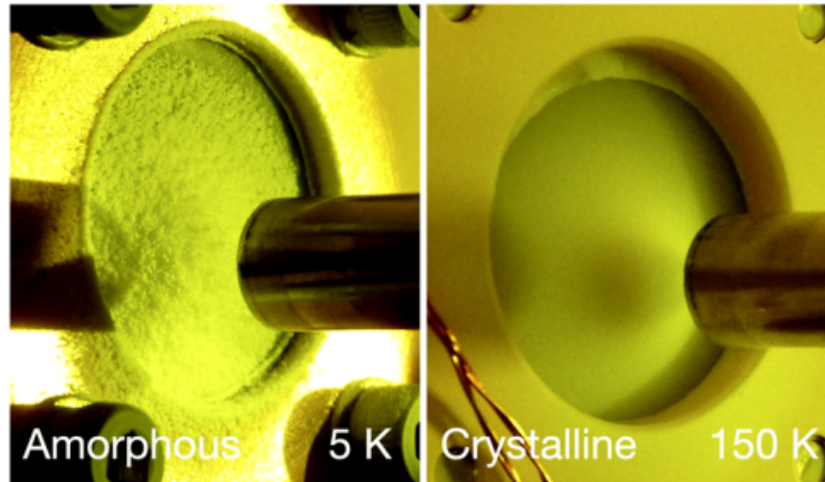


FIGURE 3.26: Images comparing amorphous and crystalline ices. Crystalline ice has a smoother texture due to the hexagonal structure of water particles compared with those in amorphous ice. Credit: Prialnik and Jewitt (2022).

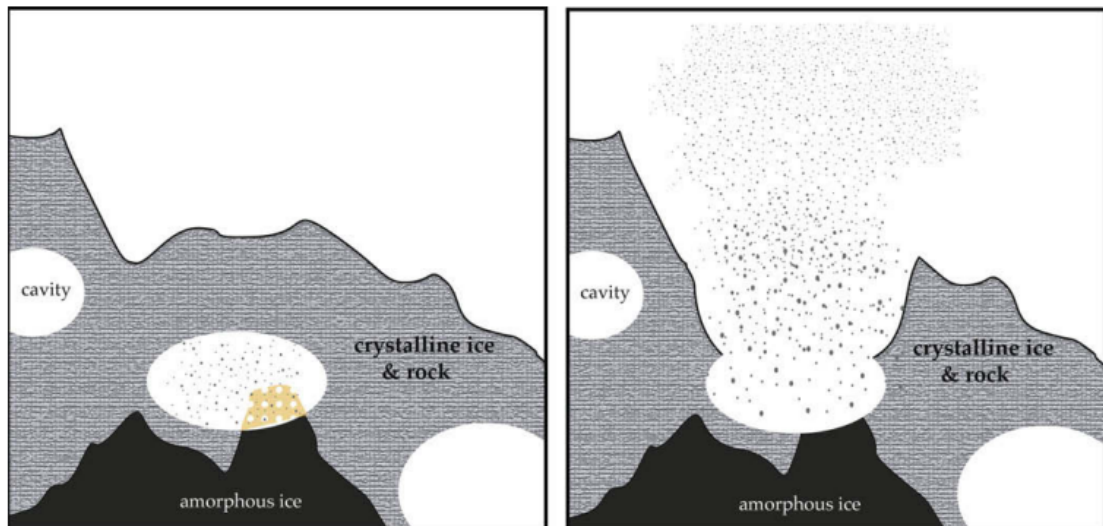


FIGURE 3.27: Diagram depicting how crystallisation of AWI into CWI could increase internal pressure in cavities, leading to an outburst. Credit: Reach et al. (2010).

dust production rate consistent with those calculated in Fulle (1992) would be sufficient to erode the surface to maintain outbursts (Enzian et al. 1997).

Gases trapped within the amorphous structure would be expelled following the phase change, building up pressure with the nucleus which could cause fractures to form in the crystalline layers near the surface, allowing the gas to be released into the coma (Patashnick et al. 1974; Prialnik and Bar-Nun 1987). Objects which formed at lower temperature regions have more gas particles trapped

within the [AWI](#) structure (Meech et al. 2009).

Additionally, any dust or gas trapped within water-ice would be released (if grain sizes are sufficiently fine) via CO emission from the conversion of [AWI](#) (Lisse et al. 2022; Smoluchowski 1981). Both methods can cause the three different outburst types mentioned earlier, primarily dust and gas emission, although dust-only and gas-only emissions can occur in certain situations. Following an outburst, if no dust/rubble remains on the nucleus surface, then any expulsion of CO would result in a gas-only outburst (Lisse et al. 2022). Surface rearrangement could expel only dust if the object is not currently emitting CO (Lisse et al. 2022).

Cavities beneath the crust could exist, due to a crust of [CWI](#) forming over it, and [sublimation](#) of water-ice could occur given enough incidental sunlight in this area, increasing the pressure (Jewitt 1990; Laufer et al. 1987). Once the pressure is sufficient, the gas could break through the crust and eject gas and dust particles. This outbursting would be small and frequent, expelling a dust cover from the surface which was insulating the ices beneath - now allowing [sublimation](#) to occur (Laufer et al. 1987).

Despite being far past the [frost line](#), water-ice [sublimation](#) could still occur due to the Centaur's near circular orbit allowing continuous and regular heating of the nucleus. Estimations of the [sublimation](#) rate of water is $8.7 \times 10^{-8} \text{ kg m}^{-2} \text{ s}^{-1}$, for context, comets at $r_H = 1 \text{ AU}$ have peak rates of $4.6 \times 10^{-4} \text{ kg m}^{-2} \text{ s}^{-1}$ (Trigo-Rodríguez et al. 2008b). While far less than the peak rate, this gradual build up could cause its own distinct outburst, or contribute gas to the 'regular' outburst.

Simulations by Guilbert-Lepoutre (2012) at [heliocentric](#) distances and rotational inclination angles similar to that of [29P/SW1](#) show that the whole surface would be likely [CWI](#), although this has not been detected in the Centaur, nor possible without using in-situ observations. A crust would have likely formed due to irradiation following the object's migration towards the Sun, insulating

the ices within the nucleus (Guilbert-Lepoutre 2012). Figure 3.28 show the variations in temperature underneath the nucleus's surface over time for an object orbiting at $r_H = 8$ AU and rotational inclination angle perpendicular and parallel with the orbital plane. For an object with a rotational inclination angle perpendicular to the orbital plane (figure 3.28a), there is a gradual heating of the nucleus along the equator, with the heat penetrating deeper under the surface over time. For objects with rotational inclination angle parallel to the orbital plane (figures 3.28b and 3.28c), there is a heating/cooling cycle for both the poles and the equator, which reduces the rate of crystallisation, especially for ices deep within the crust. Crusts of several meters of **CWI** are expected on the nuclei of **SPCs** (Jewitt 1990; Schmitt et al. 1989). **29P/SW1** is nearer to the Sun than the simulation results shown here, and its inclination angle is somewhere between the different inclinations presented. We can therefore expect some seasonality in the activity due to an intermittent heating/cooling underneath the surface, although it would not be as pronounced as what is shown in figures 3.28b and 3.28c. This cycle could preserve the **AWI** underneath the surface and extend the lifespan of the activity on the object (Guilbert-Lepoutre 2012).

For an object with radius ~ 30 km, like **29P/SW1**, it would take $60 - 1000$ Myr for all **AWI** to be converted into **CWI**, far greater than the Centaur's dynamical age of ~ 10 Myr (Guilbert-Lepoutre 2012; Lisse et al. 2022), there could be an ample supply remaining which drives the activity to the present day and beyond. Other objects within the **JFC** Gateway Region are much smaller than **29P/SW1**, and would have exhausted their supply of **AWI** within 6 Myr of their evolution to be a Centaur (Lisse et al. 2022). These other objects are not continuously active like **29P/SW1** (Sarid et al. 2019), given the lack of available **AWI**, their activity now must be driven by the sublimation of **CWI** (Lisse et al. 2022). Simulations show that for an object with orbital and rotational parameters like **29P/SW1**, the depth of crystallisation could reach > 50 m given time - this is likely greater than the radius of the Centaur, thus making all amorphous ices within the nucleus eligible for crystallisation (Guilbert-Lepoutre

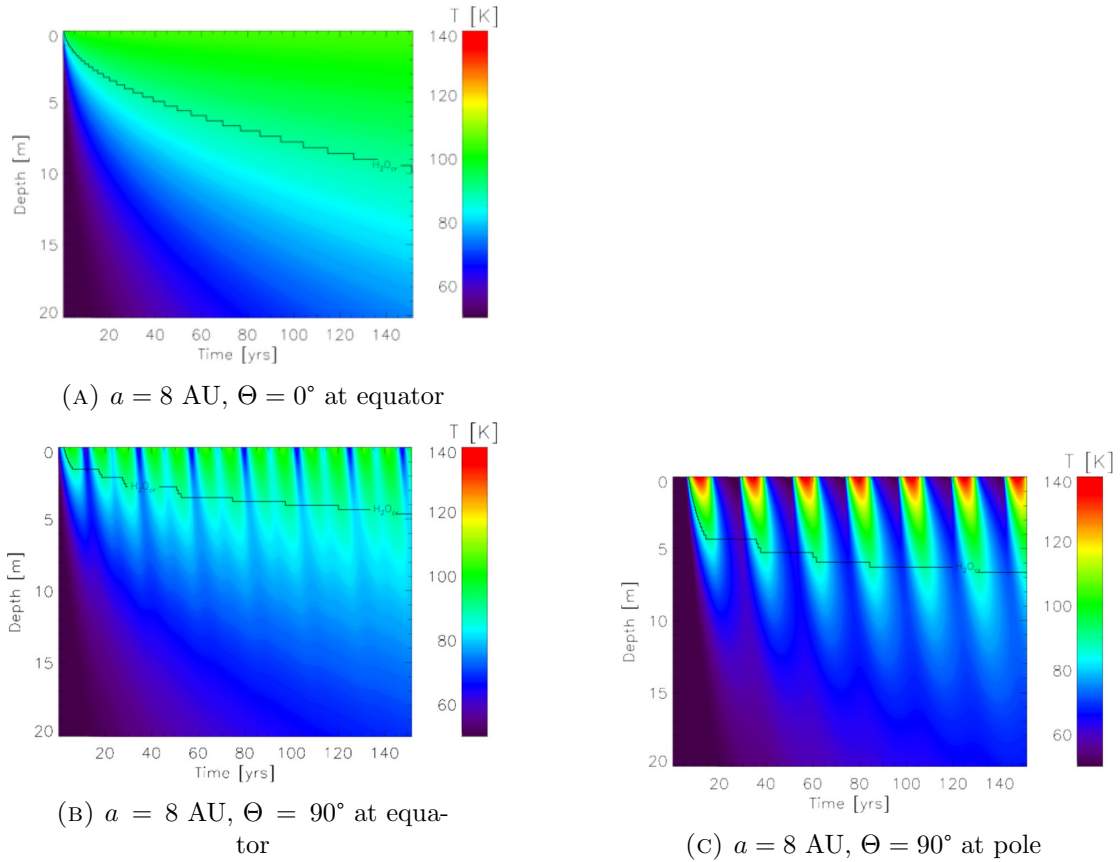


FIGURE 3.28: Temperature at various depths within a nucleus over time.

[Sublimation](#) depth of water is shown as a black line. Semi-major axis (a) and inclination angles (Θ) are specified in each figure. Credit: Guilbert-Lepoutre (2012)

2012). Approximately 35 – 50% of 29P/SW1's [AWI](#) has been converted into [CWI](#), with an estimated crystallisation timescale of ~ 62 Myr for its whole supply (Lisse et al. 2022) - these proportions are vastly different to the internal structures of other [SPCs](#) due to 29P/SW1's large nuclear size.

There are issues with proposing that [AWI](#) to [CWI](#) is the mechanism driving the outbursts, given that it is not possible to discover if the Centaur has a reservoir of [AWI](#) remotely or if it could survive long term (Gronkowski 2014). Additionally, contamination by other species within the [AWI](#) structure can drastically reduce the energy released following the conversion into [CWI](#), even to the point of becoming an endothermic reaction (Kouchi and Sirono 2001). The proportion of impurities within the structure to reduce its exothermic properties is in line with what is expected from comets and interstellar dust. A recent study

by (Kushwaha et al. 2025) shows that the crystallisation process only becomes endothermic when $\text{CO}/\text{H}_2\text{O}$ and $\text{CO}_2/\text{H}_2\text{O}$ ratios are $> 80\%$ and $> 25\%$, respectively, far above proportions seen in comet nuclei. They note that no other studies have been found investigating the exothermicity of [AWI](#) crystallisation since 2001 and that further research is required.

It is difficult to detect the presence of [AWI](#) in objects, as objects with surface [AWI](#) are at large [heliocentric](#) distances and thus difficult to observe (Jewitt 1990). Due to a comet/Centaur's formation at the far reaches of the [SS](#), the water-ice formed at these low temperatures should be in phase of [AWI](#). There is also no evidence that [AWI](#) is not present on comets.

3.4.1.2 Cryovolcanism

Some have suggested that [AWI](#) to [CWI](#) conversion would produce insufficient energy to cause the regular, immense eruptions observed by [29P/SW1](#) (Gronkowski 2014; Miles 2016b). This has led to investigations into different mechanisms that could better explain its activity.

Numerous studies have proposed that liquid exists beneath the surface of objects in the [SS](#) (Carr et al. 1998; Lunine 1993; Marusiak et al. 2021; Postberg et al. 2018). In the cases of Jupiter's moon Europa and Saturn's moon Enceladus, tidal forces caused by the parent bodies would primarily induce internal heating to create a sub-surface ocean. For objects generally experiencing less intense tidal forces, such as comets, the source of this heating would be reliant on insolation or radioactive decay from elements within the nucleus. ^{26}Al along with other radioactive isotopes could produce sufficient internal heating to cause water-ice to form for objects with nuclear radius greater than 30 km (Podolak and Prialnik 2006). Furthermore, it is possible that the energy produced from the exothermic crystallisation of [AWI](#) could be used to trigger these processes.

A slowly rotating nucleus would be required to ensure that solar heating penetrates deep enough into the nucleus, an object with rotational period ~ 60 d, as

29P/SW1 is proposed to be, would be sufficiently slow to trigger this mechanism (Miles 2016a).

Miles (2016b) suggests that beneath the crust, 29P/SW1 has reserves of liquid methane (CH_4) and CO gas dissolved, with pressure increasing over time due to further methane ice melting. Methane would melt at pressures of > 12 kPa and temperature $T \sim 90$ K (Miles 2016a). CO_2 dissolved in liquid methanol (CH_3OH) could also drive activity in a similar method (Miles 2016a).

Once the pressure within the cavity containing the cryomagma exceeds the crust tensile strength, 10 – 200 kPa, the material is able to be expelled from the nucleus. Due to the sudden decrease in pressure, the liquid methane freezes, causing a short and intense ejection of material. The surface crust can subsequently reseal, leading to pressure being able to increase again, repeating the cycle. Figure 3.29 shows diagrams of this process. Observed from Earth, these outbursts would have surge times of 10 – 20 min (Belton et al. 2008; Miles 2016a).

Numerous sources of cryomagma have been suggested throughout the nucleus. If all outbursts originated from a single source, the periodicity would have likely been detected with the plethora of data available since 1927 (Miles 2016a). Activity has been detected to originate from specific locations on the nucleus, with migration over time (Miles 2016a; Whipple 1980). Miles (2016a) assumes that the outbursts are triggered by the sub-solar point on the surface. This would therefore suggest that the periodicity of the outbursts is directly related to the rotational period of the nucleus. Miles found via period searching that there are six discrete sources on the surface of the nucleus responsible for the outbursts.

3.4.1.3 Other Mechanisms

Another proposed mechanism involves outbursts being triggered via nearby satellites brushing past the dust layer on the Centaur, expelling this material into the coma (Medvedev and Pavlov 2023). Related to the outbursts being driven by collisions, Whipple (1980) suggests that multi-outburst events could

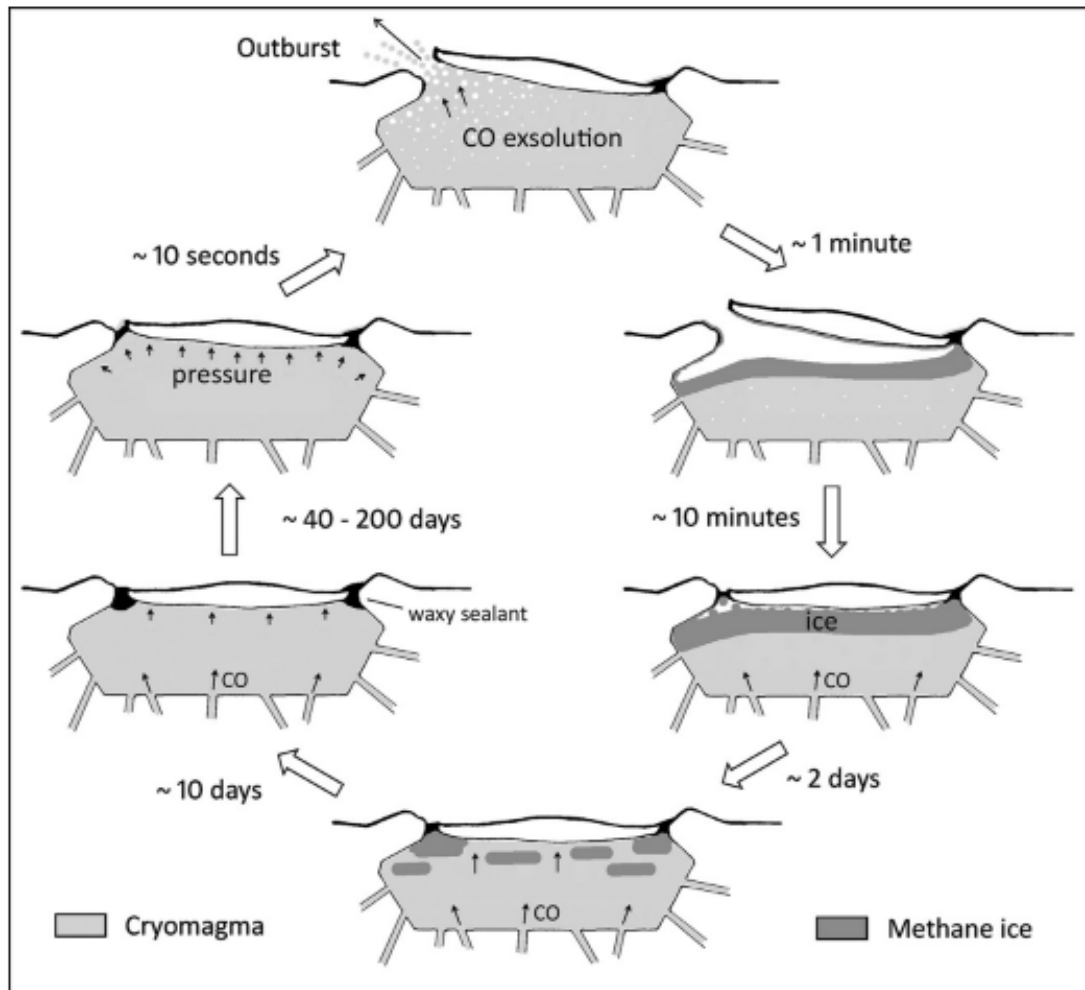


FIGURE 3.29: Diagrams depicting the proposed method that cryovolcanism could drive the observed outbursts of [29P/SW1](#). Credit: Miles ([2016b](#)).

be triggered by parts of the nucleus crust that were thrown outwards by an outburst could fall back onto the nucleus, revealing more [volatile](#) ices, and causing another outburst. Due to the large nucleus size, the escape velocity would likely be greater than the velocities of large particles being emitted during outbursts.

3.4.1.4 Comparison of Mechanisms

Table [3.9](#) summarises key features of an outburst triggered by crystallisation of [AWI](#) and via cryovolcanism.

Numerous parameters listed are similar in the two mechanisms, with major differences appearing in the conditions required for an outburst to occur, such as

pressure and temperature. Cryovolcanism could cause outbursts at lower temperatures compared with crystallisation, although a far higher pressure is required, as crystallisation can occur in a near-vacuum.

3.4.2 Outburst Structure

Jets and shell structures have been identified in [29P/SW1](#)'s coma during/following an outburst (Faggi et al. [2024](#); Lin [2023](#); Shubina et al. [2023](#)). In the solar direction, Betzler ([2023a](#)) found fan-like structures in the coma following an outburst. Following observations by [JWST](#)/NIRSpec, heterogenous jets of CO and CO₂ were detected emitting from the Centaur's nucleus (Faggi et al. [2024](#)), see fig. [3.30](#). Jets were detected in north, south, and frontal directions, each with different proportions of the molecules being expelled. Polar sources of outburst are the most likely location for strong emissions as they are illuminated permanently for half of the Centaur's year (Kossacki and Szutowicz [2013](#)) due to the assumed rotational axis inclination angle of 65° (Whipple [1980](#)).

Sunlight likely triggered the frontal jets with production rate ratio $Q_{\text{CO}}/Q_{\text{CO}_2} \approx 55$, both CO and CO₂ appeared in these jets (Faggi et al. [2024](#)). There is a preference for sunwards emission to contain dust grains (Schambeau et al. [2021](#)).

Modelling shows that equatorial emissions can occur if the nucleus is fine grained and CO-rich (Kossacki and Szutowicz [2013](#)). The southern jet contained only CO₂, while the northern jet contained both species at a ratio $Q_{\text{CO}}/Q_{\text{CO}_2} \approx 257$, a far greater proportion of CO than the frontal jet, both jets had similar levels of CO₂ (Faggi et al. [2024](#)). Modelling by Enzian et al. ([1997](#)) shows that outbursts originate from the equatorial region and south pole based on activity driven by [AWI](#) to [CWI](#) phase transition and [sublimation](#) of [volatile](#) ices. Faggi et al. ([2024](#)) gives two suggestions why the jets have different compositions, either the object's composition is not homogenous (due to surface changes or CO depletion on one pole) or the object is [bilobate](#) (an object was formed by two colliding objects of different compositions).

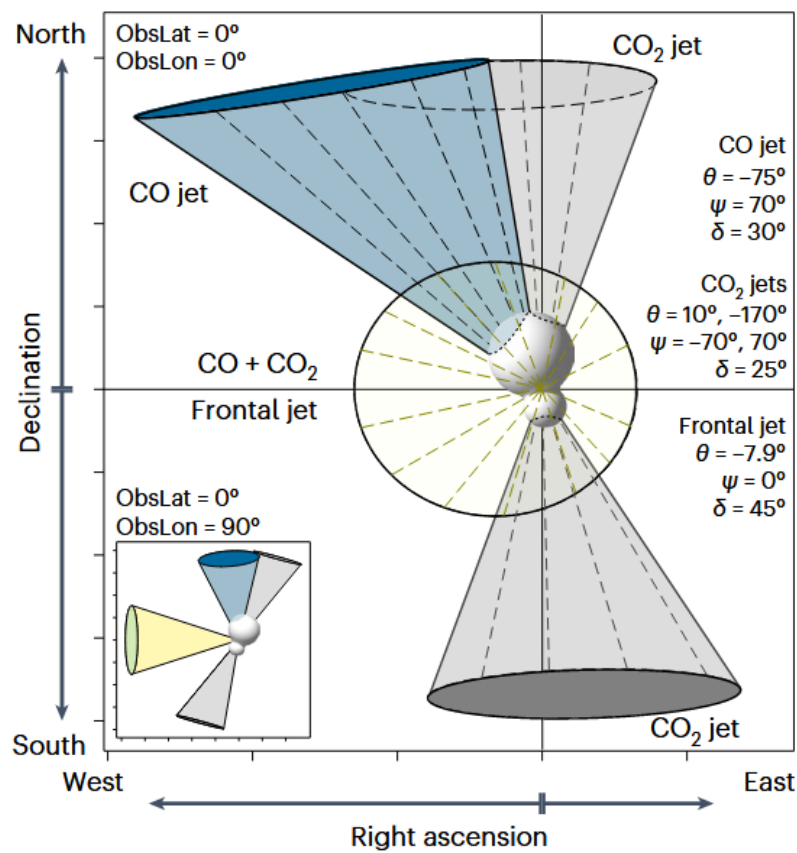


FIGURE 3.30: CO and CO₂ jets detected with observations made by [JWST](#).
Credit: Faggi et al. (2024).

Wing structures have been detected in the coma following an outburst towards south-south easterly direction, curving towards the south-easterly direction (Schambeau et al. 2021). Schambeau et al. (2021) suggests that solar radiation pressure and gravity from the Centaur causes the curve, forming a dust tail structure.

3.4.3 Coma Composition

Coma analysis of [29P/SW1](#) shows it is dominated by CO, with very low proportion of CO₂, with a production rate ratio of $\text{CO}/\text{CO}_2 > 84$ (Cochran et al. 1980; Fulle 1992; Harrington Pinto et al. 2022). CO line profiles have been detected in [29P/SW1](#) during active and quiescent periods, primarily in the subsolar region (Bockelée-Morvan et al. 2022), suggesting that incident solar radiation triggers the expulsion of CO. This difference in coma composition compared with other Centaurs and comets could be due to the nuclear composition, or due to

its large [heliocentric](#) distance favouring activity driven by the more [volatile](#) CO (Harrington Pinto et al. [2022](#)). [29P/SW1](#) had the highest CO/CO₂ ratio of all the objects analysed in the study by Harrington Pinto et al. ([2022](#)).

Proportions of hydrogen cyanide (HCN) production rate versus water production rate is around ten times greater in [29P/SW1](#) than comets at [heliocentric](#) distances of ~ 1 AU (Bockelée-Morvan et al. [2022](#)). The polymerisation of HCN could raise internal temperatures from 100 K to 150 K, in this case sufficient to trigger water-ice [sublimation](#) (Rettig et al. [1992](#)). This heating could provide the trigger for outbursts to occur. It is believed that the nucleus does not directly contribute to the production of HCN, these compounds are produced via the [sublimation](#) of icy grains released into the coma (Bockelée-Morvan et al. [2022](#)).

The coma is persistent around the nucleus even during periods of [quiescence](#) due to continuous mass loss, and can extend up to 10^5 km (Jewitt [1990](#); Trigo-Rodríguez et al. [2008b](#)). This continuous coma could be due to the [sublimation](#) of the [CWI](#) crust at the [sub-solar point](#) (Jewitt [1990](#)). A mass loss rate to maintain this coma is $\frac{dm}{dt} \sim 10 \text{ kg s}^{-1}$ (Jewitt [1990](#)).

Material ejected during an outburst, naturally, is a reflection of the composition of the nucleus itself. [Volatile](#) ices, such as CO and CO₂, are believed to drive the outbursts, with both species detected in observations (Faggi et al. [2024](#); Jewitt [1990](#)). While water ice is present within the Centaur's nucleus, water [sublimation](#) does not drive the outburst mechanisms as the object never crosses the [frost line](#).

Jewitt ([2009](#)) estimates the mass-loss rate of CO to be between 1000 to 2000 kg s⁻¹. CO production rate has been estimated to be $Q_{\text{CO}} = (2.9 - 5.6) \times 10^{28} \text{ s}^{-1}$, equivalent to 1400 – 2600 kg s⁻¹ (Bockelée-Morvan et al. [2022](#); Enzian et al. [1997](#)). A [sublimation](#) rate of CO has been estimated to be $4.6 \times 10^{-4} \text{ kg m}^{-2} \text{ s}^{-1}$, at temperatures of 38 K (Trigo-Rodríguez et al. [2008b](#)). The CO production rate is at the lower end of this range during a quiescent period, with Wierchos and Womack ([2020](#)) suggesting that the upper limit during this period to

be $(3.6 \pm 0.7) \times 10^{28} \text{ s}^{-1}$. Higher production levels of CO have been correlated with the time the coma appears brightest (Bockelée-Morvan et al. 2022), although this is not always true (Wierzechos and Womack 2020). Some outbursts display heightened levels of CO production, while others do not show any change (Wierzechos and Womack 2020). Outburst events which had an elevated Q_{CO} sometimes had different shaped lightcurves, having a more gradual increase and decay of brightness than larger and more explosive outbursts (Wierzechos and Womack 2020). The surface of the Centaur is likely depleted of CO and CO₂ due to their volatility at low temperatures (Trigo-Rodríguez et al. 2008b).

Spectroscopic analysis shows H₂O production rate being $\sim 120 \text{ kg s}^{-1}$, roughly 10% of the production rate of CO, although the water line is not always visible (Bockelée-Morvan et al. 2022). Measurements show that there is a constant ratio of the H₂O/CO lines (Bockelée-Morvan et al. 2022).

Proportion of carbon dioxide in the coma appear to be significantly lower than those for other comets investigated by Ootsubo et al. (2012). With a production rate $Q(\text{CO}_2) < 4 \times 10^{26}$ (Ootsubo et al. 2012), while the sublimation rate is similar to that for CO, albeit at $T = 113 \text{ K}$ (Trigo-Rodríguez et al. 2008a). $Q(\text{CO}_2)/Q(\text{CO})$ ratio is only 1%, 10 times less than the water to carbon monoxide production rate ratio (Ootsubo et al. 2012).

TABLE 3.6: B–V colour measurements of comet 29P organised by colour index and date.

Value	Aperture (")	Date	Ref.
0.77	101.0	1958-12-04	1
0.72	67.0	1958-12-04	1
0.95	88.0	1976-12-17	2
1.06	88.0	1976-12-17	2
0.98	88.0	1976-12-22	2
0.62	88.0	1976-12-26	2
0.68	88.0	1977-02-09	2
0.80	7.8	1980–1981	3
0.49±0.02	0.7	1987-08-22	4
0.72±0.03	6.6	2002-09-08	5
0.79±0.03	1.1	2002-09-08	5
0.64±0.09	5.4	2006-12	6
0.54±0.08	5.4	2006-12	6
0.76±0.02	5.7	2010-02-05	7
0.82±0.02	5.7	2010-02-16	7
0.89±0.01	5.0	2011-04-05	8
0.78±0.01	5.0	2011-04-06	8
0.79±0.04	1.1	2012-02-20	9
0.72±0.03	6.6	2012-02-20	9
0.85	3.0	2017-07-30	10
0.80	3.0	2017-07-31	10
0.85	3.0	2017-08-01	10
0.77	Mean Value		

¹ Walker ([1959](#))

² Kiselev and Chernova ([1979](#))

³ Hartmann et al. ([1982](#))

⁴ Meech et al. ([1993](#))

⁵ Jewitt ([2009](#))

⁶ Ivanova et al. ([2009](#))

⁷ Miles et al. ([2016](#))

⁸ Shi et al. ([2014](#))

⁹ Ivanova et al. ([2016](#))

¹⁰ Kokhirova et al. ([2020](#))

TABLE 3.7: R–I colour measurements of comet 29P organised by colour index and date.

Value	Aperture (")	Date	Source
0.49±0.02	0.7	1987-08-22	1
0.52±0.03	1.1	2002-09-08	2
0.48±0.03	6.6	2002-09-08	2
0.76	3	2017-07-28	3
0.57	3	2017-07-29	3
0.54	3	2017-07-30	3
0.45	3	2017-07-31	3
0.50	3	2017-08-01	3
0.54	Mean Value		

¹ Meech et al. (1993)

² Jewitt (2009)

³ Kokhirova et al. (2020)

TABLE 3.8: V–R colour measurements of comet 29P organised by colour index and date.

Value	Aperture (")	Date	Source
0.51±0.01	0.7	1987-08-22	1
0.49±0.01	0.7	1987-08-26	1
0.51±0.03	1.1	2002-09-08	2
0.47±0.03	3.3	2002-09-08	2
0.48±0.01	5.0	2011-04-06	3
0.64±0.03	1.1	2012-02-20	4
0.62±0.02	2.2	2012-02-20	4
0.59	3.0	2017-07-28	5
0.50	3.0	2017-07-29	5
0.47	3.0	2017-07-30	5
0.47	3.0	2017-07-31	5
0.60	3.0	2017-08-01	5
0.53	Mean Value		

¹ Meech et al. (1993)

² Jewitt (2009)

³ Shi et al. (2014)

⁴ Ivanova et al. (2016)

⁵ Kokhirova et al. (2020)

TABLE 3.9: Comparison of expected properties of outbursts if caused by [AWI](#) to [CWI](#) conversion or due to cryovolcanism.

	AWI→CWI	Cryovolcanism
Surge time	2 – 5 hr ^a	10 min to 2 hr ^{b,c}
Material ejected	Dust and gas ^d	Dust and gas ^{c,5}
Maximum energy	$\sim 10^4$ J kg ^{-1d}	$\sim 1.5 \times 10^{12}$ J ^c
Periodicity	Related to rotational period ^f	Related to rotational period ^c
Temperature required	135 – 155 K ^g	65 – 95 K for liquid CH ₄ and 150 – 200 K for liquid CH ₃ OH ^c
Pressure required	> 1 Pa ^h	10 – 200 kPa ^e
Source depth	> 5 – 10 m ⁱ	10 – 100 m ^b

^a Sekanina ([1990](#))

^b Belton et al. ([2008](#))

^c Miles ([2016a](#))

^d Prialnik and Jewitt ([2022](#))

^e Miles ([2016b](#))

^f Sekanina ([1990](#))

^g Prialnik and Bar-Nun ([1992](#))

^h Laufer et al. ([1987](#))

ⁱ Guilbert-Lepoutre ([2012](#))

TABLE 3.10: Outgassing and [sublimation](#) properties by species

Species	Production rate (molecules s ⁻¹)	Mass loss rate (kg s ⁻¹)	Sublimation rate (kg m ⁻² s ⁻¹)	Sublimation temperature (K)	$Q(X)/Q(\text{CO})$ (%)
CO	10 ^{28a}	1400–2600 ^b	4.6×10^{-4c}	38	100
CO ₂	$< 4 \times 10^{26d}$	—	4.6×10^{-4c}	113	$\sim 1^4$
H ₂ O	$\sim 4 \times 10^{27b}$	120 ^b	8.7×10^{-8c}	150	10 ^b

^a Enzian et al. ([1997](#))
^b Bockelée-Morvan et al. ([2022](#))
^c Trigo-Rodríguez et al. ([2008a](#))
^d Ootsubo et al. ([2012](#))

3.4.4 Dust Production

The dust released during quiescent and active periods are primarily amorphous minerals (Schambeau et al. 2015). It is possible to estimate the rate at which dust is produced and ejected. First introduced by A'Hearn et al. (1984), $Af\rho$ is a reflection of how active an object is. A represents the albedo of the dust grains ejected from the nucleus, f is the filling factor, and ρ is the radius of the photometric aperture.

This expression is defined by Lin (2023) as,

$$Af\rho = (2.467 \times 10^{19}) \frac{r_h \Delta^2}{\rho} 10^{0.4(m_\odot - m)} \quad (3.17)$$

where r_h and Δ are the [heliocentric](#) and [geocentric](#) distances in AU, ρ is photometric aperture in arcseconds, and $m_\odot$ and m are the solar and cometary magnitudes, respectively. The 2.467×10^{19} factor converts the units used in this expression to be more convenient, rather than km for [geocentric](#) distance and aperture radius. $Af\rho$ assumes a spherically-symmetrical emission (Schambeau et al. 2017). Note: $Af\rho$ is measured in cm.

When the object is in a quiescent phase, $Af\rho = 636 \pm 64$ cm, and when active, $Af\rho = 17563 \pm 982$ cm (Shubina et al. 2023). Even during [quiescence](#), [29P/SW1](#) has a higher dust production rate than many other comets (Clements and Fernandez 2021).

Using $Af\rho$ values, Schambeau et al. (2017) gives an expression to estimate the dust production rate.

$$Q_{dust} = \frac{8a\rho_d v_d (Af\rho)}{3p} \quad (3.18)$$

where a is dust grain radius, ρ_d is the dust grain density, v_d is expansion velocity of the dust grains, and p is the geometric albedo of the dust.

The increase in dust production is very rapid during an outburst, even in outbursts with short intervals between them, suggesting that outbursts will very

likely always contain large proportions of dust. This rate decreases after the outburst has concluded, but not quickly, after almost a week, the dust production rate is ~ 65 times greater than during quiescent periods (Lin and Ip 2021), increasing to $38 \pm 7 \text{ kg s}^{-1}$ over several days (Clements and Fernandez 2021), even measured upwards of 660 kg s^{-1} (Perna et al. 2015).

Dust production rate is variable during quiescent periods, with Bockelée-Morvan et al. (2022) finding a 2.5 times difference between outbursts occurring a few years apart. Quiescent dust production rate measured can vary from $4.6\text{--}20 \text{ kg s}^{-1}$ (Clements and Fernandez 2021; Voitko et al. 2022).

The total mass ejected can be calculated via,

$$M = \frac{4}{3} \rho_d a C_{dust} \quad (3.19)$$

where C_{dust} is the total scattering cross section of the dust grains (Schambeau et al. 2017).

Fulle (1992) calculated 29P/SW1's mass loss rate to be $600 \pm 300 \text{ kg s}^{-1}$, which contributes $6 \pm 3\%$ of the dust required to resupply the interplanetary cloud's dust proportions. Lin (2023) calculates the total ejected mass during an outburst, $M = 4.1 \times 10^7 - 2.7 \times 10^9 \text{ kg}$. A maximum gas velocity of 500 m s^{-1} has been observed in 29P/SW1, with a mean velocity $\bar{v}_{dust} = 300 \text{ m s}^{-1}$ (Trigo-Rodríguez et al. 2008b), with a persistent outflow velocity of $v = 50 - 100 \text{ m s}^{-1}$ (Miles and Faillace 2011).

3.4.5 Outburst Trends

Regular outbursts occur, with periodicity detected only during some time spans. For the period of 2002–2007, Trigo-Rodríguez et al. (2008b) found no outbursting periodicity. As discussed in sect. 3.3.1.1, outbursting periodicities were used to calculate a rotational period of $\sim 57 \text{ d}$, this was detected in 2010–2014 period (Miles 2016a; Stoddard-Jones 2021). Miles (2016a) suggests that this is due to

certain outburst sources being inactive due to [29P/SW1](#)'s rotational inclination angle causing seasonality. If this is the case, the 2025–26 apparition should have similar periodicity. Mini-outbursts, outbursts with intensity $\Delta m < 1$ mag, have been noted to occur regularly (Gronkowski [2014](#); Miles et al. [2016](#)).

Outbursts have often been detected to occur soon after one another, these are as a [Multi-Outburst Events \(MOE\)](#) (Kelley et al. [2021a](#); Miles [2024b](#); Ye et al. [2019c](#)). It is believed that an intense outburst triggers the subsequent outbursts, although the precise mechanism is unknown. Roughly 5 days following an outburst, there is a large possibility of another outbursts with amplitude > 2 mag (Whipple [1980](#)).

Intensity of [29P/SW1](#)'s outbursts varies before and after [perihelion](#). Before [perihelion](#), there are more intense outbursts, which results in an asymmetrical lightcurve pre-perihelion and post-perihelion (Betzler [2023a](#)). This was first suggested by Whipple ([1980](#)) who noted that activity while approaching [perihelion](#) is greater than that of following [perihelion](#), while also mentioning that the orbital position of the object is generally unrelated to the maximum activity exhibited. Despite the variation in intensity, the number of outbursts pre-perihelion and post-perihelion remains roughly constant (Betzler [2023a](#)). CO gas production rate is greater when at either [perihelion](#) or [aphelion](#) (Enzian et al. [1997](#)).

Colours of outburst emissions can vary: a multi-outburst event in 2017 appeared redder, while smaller outbursts appear more neutral according to Kareta et al. ([2025](#)), likely due to the material being expelled from the nucleus. Voitko et al. ([2022](#)) detected a bluer colour during a medium outburst.

3.5 Observational Campaigns of 29P/SW1

3.5.1 British Astronomical Association's Mission 29P

The [British Astronomical Association](#) has an observing campaign 'Mission 29P', directed and formed by Miles (2024b). The aim of this mission is to ensure regular imaging of the object, and to notify others when outbursts are detected to increase the frequency of imaging. This observing campaign utilises the availability of telescope time of amateur astronomers, and the high quality, research grade telescopes available to professional astronomers. Miles regularly updates the page with new images and data points to the long-term light-curve 3.31.

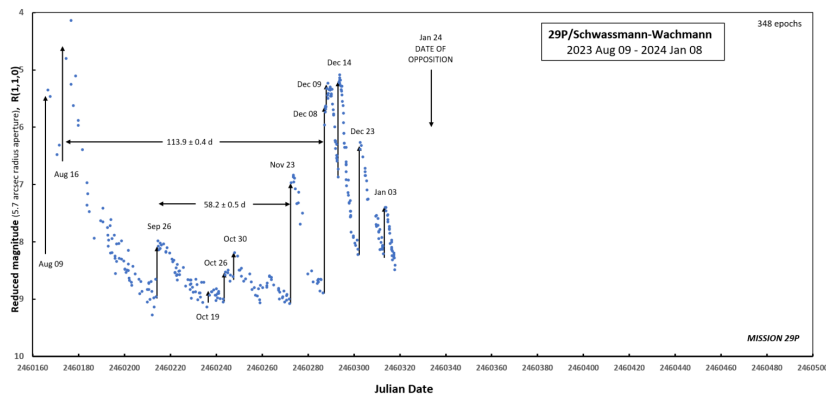


FIGURE 3.31: Lightcurve of 29P/SW1, vertical arrows represent outbursts. Credit: Miles (2024b).

This vigorous observing has resulted in discovering numerous new outbursts, including ATels (Betzler 2023b; Kelley et al. 2021a, 2023a, 2021c; Lin and Ip 2021; Sharma et al. 2021a,b). While the surge period itself is difficult to image due to how rapid the brightness increases, the fallback period is well imaged.

Images obtained by amateur astronomers are not used in the dataset analysed in this thesis, nonetheless, they have been essential to schedule observations by the LCO network as soon as possible following a detected outburst.

3.5.2 Comet Chasers and LCO

As discussed in sect. 2.4, Comet Chasers is an educational outreach programme to engage students in real astronomy. Part of this programme is to enable students in school to access the LCO network, to image objects and contribute to real research (see sect. 2.4.2 for further details). This has been an invaluable asset to the LCO 29P/SW1 dataset, leading to ample imaging of the Centaur.

3191 data points (72% of whole dataset) used in this thesis were obtained by observers in conjunction with Comet Chasers, either by schools themselves, or supporting astronomers. The regular and intense observing campaign ran via the Comet Chasers programme has allowed a previously impossible deep dive into the trends and patterns the outbursts exhibit.

Note, schools involved in the workshop feedback in this thesis did not contribute to this dataset. Workshops were treated as investigations into the introduction into Comet Chasers. Existing schools taking part in the programme provided the images.

The LCO network is a world-wide network of robotic telescopes with an observatory on (almost) every continent, able to schedule and fulfil observation requests without human intervention. Numerous identical telescope set-ups allow for consistent imaging.

3.5.2.1 2m MuSCAT

There are two 2m Ritchey-Chretien Cassegrain telescopes with MuSCAT cameras (Narita et al. 2020) in the LCO network, located at Faulkes Telescope North at Haleakala Observatory (Mauna Kea, Hawaii, USA), and Faulkes Telescope South at Siding Spring Observatory (NSW, Australia).

Differing from the other telescope classes, the MuSCAT camera can obtain images in different filters (SDSS g' , r' , i' , and PanSTARRS zs) simultaneously.

TABLE 3.11: Observatory sites, codes, locations, time zones, and telescope counts.

Site	Code	Country	Time zone	0.4m	1.0m	2.0m
Siding Spring Observatory	COJ	NSW, Australia	UTC+10	2	2	1
South African Astronomical Observatory	CPT	South Africa	UTC+2	1	3	0
Wise Observatory	TLV	Israel	UTC+2	0	1	0
Teide Observatory	TFN	Tenerife, Spain	UTC	2	2	0
Cerro Tololo Interamerican Observatory	LSC	Chile	UTC-3	2	3	0
McDonald Observatory	ELP	TX, USA	UTC-6	3	2	0
Haleakalā Observatory	OGG	HI, USA	UTC-10	2	0	1

The incoming light is split by lenses using their respective filters and detected in their individual channels, see figure 3.32.

The field of view is $9.1' \times 9.1'$ and a pixel scale of $0.27''/\text{pixel}$.

Despite being designed to analyse exoplanet atmospheres, it is an extremely useful camera to image comets. Due to comets moving more quickly across the sky than stars, their positions can vastly change between exposures. The ability to image in numerous filters simultaneously allows for better colour analysis and reduces the risk of failed observation requests due to time limitations.

While the [MuSCAT](#) camera is currently on the 2m class telescopes, they were installed on [FTN](#) and [FTS](#) in 2020 and 2023, respectively. Any data obtained using the 2m telescopes before these dates used the Spectral camera. This camera could only image in one filter at a time. Field of view: $10.5' \times 10.5'$ and a pixel scale of $0.152''/\text{pixel}$.

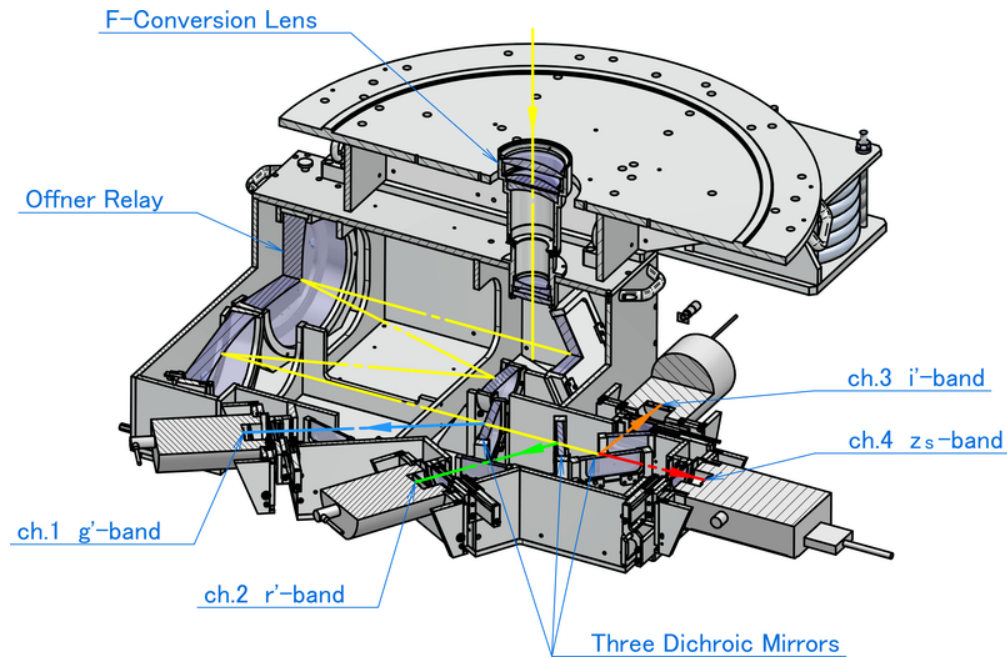


FIGURE 3.32: Cutaway of the [MuSCAT](#) camera. The path of the incoming light is shown and how it is split into the different filters. Credit: (Narita et al. [2020](#)).

3.5.2.2 1m Sinistro

The 1m Ritchey-Chretien Cassegrain telescopes with Sinistro cameras are situated in 5 [LCO](#) observatories; 2 in Siding Springs (Australia), 3 in Sutherland (South Africa), 3 in Cerro Tololo (Chile), 2 in McDonald (Texas, USA), 2 in Teide (Spain), and 2 in Haleakala (Hawaii, USA).

Two sets of broadband filters are available on these telescopes; SDSS/Pan-STARRS (u' , g' , r' , i' , zs , Y , w), and Johnson-Cousins (U , B , V , R , I). Unlike the [MuSCAT](#) camera, the Sinistro can only image in one filter at a time.

The field of view is $26.5' \times 26.5'$ and a pixel scale of $0.389''/\text{pixel}$.

3.5.2.3 0.4m QHY600

There are 6 [LCO](#) observatories containing a 0.4m Cassegrain (Planetwave Delta Rho 350) telescope with QHY600 CMOS camera (Harbeck et al. [2024](#)), 2 in Siding Springs (Australia), 1 in Sutherland (South Africa), 2 in Cerro Tololo

(Chile), 1 in McDonald (Texas, USA), 2 in Teide (Spain), and 2 in Haleakala (Hawaii, USA).

The field of view is $1.9^\circ \times 1.2^\circ$ and a pixel scale of $0.74''/\text{pixel}$.

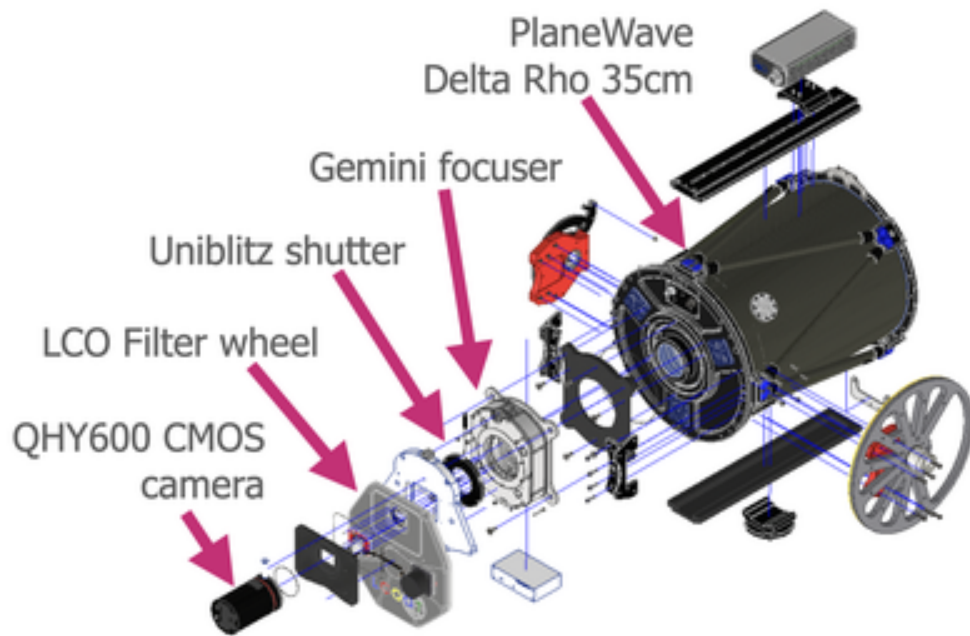


FIGURE 3.33: Exploded view of the telescope and supplementary instruments. Credit: Harbeck et al. (2024).

3.5.3 Skalnaté Pleso Observing Trip

During March 2024, an Europlanet grant enabled an observing trip to Skalnaté Pleso Observatory, Slovakia. This trip consisted of 3 nights observing [29P/SW1](#). An outburst was expected to be imminent during this time as the brightness of the object was at a reduced magnitude of $R(1, 1, 0) = 9.0$ mag (Miles [2024a](#)). The object does not maintain a dim brightness for very long, before the next outburst occurs.

Established in 1943, Skalnaté Pleso Observatory lies 1786m above sea level in the Tatra Mountains in northern Slovakia ([Skalnate Pleso Observatory 2025](#)). Two telescopes are at this site, a 0.61m automated Newtonian telescope and

a 1.3m Nasmyth-Cassegrain telescope (*Skalnate Pleso Observatory 2025*). Unfortunately, the 1.3m telescope was undergoing repairs during the trip, but the 0.61m telescope more than sufficed.

Due to poor weather, no observing was possible during night 1. Weather improved for the next two nights. Night 2 images showed the Centaur at its minimum brightness.

Night 3 was an unexpected success. The telescope imaged the onset of an outburst and subsequent post-outburst period. A message was sent into the [29P/SW1](#) mailing list to notify other observers that an outburst had taken place.

These observations are included in the [29P/SW1](#) dataset used in this thesis.

3.6 Summary

Given the transitional nature of Centaurs between [TNO](#) and [JFC](#) (Sarid et al. 2019), [29P/SW1](#) gives a unique insight into how activity may develop as an object migrates inwards into the inner [SS](#).

It has a very large nucleus, with numerous estimates around 60 km diameter (Bockelée-Morvan et al. 2022; Kokhirova et al. 2020; Schambeau et al. 2021; Stansberry et al. 2004), and potentially a very slow rotational period, on the order of tens of days (Miles et al. 2016; Shubina et al. 2023; Stansberry et al. 2004). Combining these factors with the object's unusually circular orbit likely contribute to its unique and intense activity observed for almost a century.

Given [29P/SW1](#) has a relatively constant [heliocentric](#) distance of ~ 6 AU, very unusual for a comet, 'normal' cometary activity cannot explain why the object undergoes so many outbursting events throughout its orbit. Its unusual activity has been suggested to be driven by the crystallisation of [AWI](#) into [CWI](#), and by the expulsion of [cryomagma](#) beneath the crust.

Part I

Physics Education Research: The impact of Comet Chasers on school students

Chapter 4

Radnor Children's University

During January and February 2023, Comet Chasers conducted a series of 6 weekly workshops with students in years 3 and 4 at Radnor Primary School, Cardiff. Approximately 18 students participated in weekly workshops as part of a joint project between Cardiff Council and Cardiff University, “Passport to the City: Cardiff Children’s University”, encouraging an interest in learning over a wide range of topics, often not taught in the curriculum.

Delivery was conducted by the author and Helen Usher (Open University PhD student), with one leading every other week.

These workshops were treated as a trial for long-term interventions with students. Each workshop was a self-contained lesson (with some ongoing themes) based on different areas of astronomy, e.g. researching different galaxies, meteorite impacts, comet structure, investigating different wavelengths of light, and building and launching their own air-powered rockets.

4.1 Post-Engagement Evaluation

Due to a delay in receiving ethical approval from the Physics and Astronomy School Research Ethics Committee (SREC), the initial plan of a weekly survey was not possible. Instead, a questionnaire was completed after the final session, evaluating the students' general view of science as a school subject and the Comet Chasers programme.

It is noted that participating students' attitudes towards science might be somewhat biased, as the students who took part opted for the Comet Chasers project as part of their involvement in Cardiff Council Children's University programme. Despite this potential bias, this pilot evaluation with the students is important - it assesses how students who already enjoy [STEM](#) subjects respond to the programme.

Students were asked to take part in the questionnaire if their parents had returned a completed consent form. Their teacher suggested that the questionnaire was treated as a 1-to-1 interview, asking the students the question rather than letting them complete the form on their own. While this allowed further explanation regarding the questions being asked, it could have introduced untrue or biased sentiments due to a deliverer being directly involved. Students may have felt pressured to score the Comet Chasers programme higher than they really felt, so as to not hurt the deliverer's feelings. To try to mitigate this, it was repeated that their honest opinions were needed.

Due to these factors, this was treated as a focus group and everything mentioned by all students is discussed.

This post-engagement questionnaire was split into 3 sections: student's demographics and their interest in science in school; evaluation of the workshop/resources, and a brief summary of the programme. 9 responses were obtained following the numerous interventions. Although this is a very small sample size, indications of the students' opinions and views of the repeated engagements

and multiple workshops are valuable, especially at the early ‘pilot’ phase of the project.

4.1.1 What school year are you in?

This was asked to gauge how adaptable and appropriate the workshops were for different ages. We were aware that both year 3 and 4 students were involved in the Rador programme, although the proportion was not known - the usual Comet Chasers’ workshops were adapted before the interventions to accommodate the younger audience. Due to the small sample size, it was not useful to compare responses between different years, as they are unlikely to be representative.

Approximately half (4) of the students questioned were in Year 4, with the remainder (5) in year 3.

TABLE 4.1: Summary of school year of students gave their responses.

Year	n	%
Year 3	4	44.4%
Year 4	5	55.6%
Total	9	100%

4.1.2 What’s your favourite subject at school?

Assessing what the students enjoy most in school is important for judging how enjoyable and engaging the Comet Chasers programme is for all students. If all participants’ favourite subject is science, it is likely they would enjoy the workshops - this would not be useful from the point of view of developing Comet Chasers as it would not be clear if the resources were able to engage all students (regardless of whether they enjoy science already). Having a variety of favourite subjects selected indicates that the sample would be more reflective of a larger

population, allowing fair assessment as to how engaging the activities were for all students (including those who might have disliked science).

Despite the students choosing to take part in the Comet Chasers project, not one participant selected Science as their favourite subject in school. The questionnaire offered multiple options for a favourite subject, including an ‘Other’ section to cover any subject not included in the list. Options included: English, Welsh, Maths, Science, Art, IT, History, and Physical Education.

TABLE 4.2: Favourite school subject mentioned by Radnor Primary School students.

Favourite subject	n	%
Art	3	33.3%
Literacy	2	22.2%
Maths	3	33.3%
P.E.	1	11.1%
Total	9	100%

Overall, 3 selected Maths, 3 selected Art (including music), 2 selected Literacy, and 1 selected Physical Education. While it is not surprising that Maths was one of the most liked subjects (given the sample pool), an equal amount of students chose Art as their favourite subject, which is perhaps more surprising as it would traditionally be perceived as being more different to Science as compared to Maths. This means that the opinions expressed in the evaluations will represent a broader type of student, not just those who prefer [STEM](#) subjects.

Interestingly, ‘Literacy’ was not an option given in the questionnaire, and instead was opted as an ‘Other’ category by two students. Clearly, the school does not have specific ‘English’ lessons. Other subjects could follow similar paths, with different names applied to them.

4.1.3 What do you like about science lessons in school?

Pairing this question with that in section [4.1.4](#) gave an insight into the student’s opinion on how science lessons were conducted in their school. This would also

give a good indication to the methods of delivery which should be focussed on to encourage the students' enjoyment of the workshop, likewise what to avoid for aspects of science lessons they dislike.

As an open question, answers varied greatly. 3 of the 9 students did mention they found science fun, with varying reasons.

"Feel excited, fun, hiding education with happiness" (Year 3)

"Fun and get to do experiments" (Year 4)

"Fun and things outside [sic]..." (Year 4)

2 of the 9 suggested that they enjoy experiments.

"Testing experiments" (Year 3)

"Fun and get to do experiments" (Year 4)

One student said: *"How things work"* (Year 4)

There were also two respondents who either did not respond or say 'Not sure'.

Finally, one response did not relate too much to the question, and due to the tight time constraint trying to obtain as many responses as possible, there was not an opportunity to ask the student to clarify. *"Nice and tell you off I'm[sic] a good way"* (Year 4)

From these responses, the 'most enjoyed' parts of science lessons were the hands-on, interactive activities, which the students viewed as fun or exciting. This agrees with the assumptions we were making - creating activities designed to be more exciting and tactile will nurture an interest in science due to greater student enjoyment.

4.1.4 What don't you like about science lessons in school?

Responses to this question were quite positive. The three most positive were;

"Have to wait others to finish" (Year 4)

"Bits where stops and tidy away" (Year 3)

“Nothing”

(Year 4)

One student was quite detailed in their response, citing their least favourite aspects as: *“Hard work ,reading, don’t want to do something,[sic]”* (Year 4)

Despite this response, this student had mentioned that they found science fun in the previous question.

The final response (other than no response/not sure) cited: *“When things fail”* (Year 3)

This could be due to issues encountered during the experiment. Problems and errors due to the experimental equipment or software can easily lead to frustration in the classroom. Ensuring that the equipment is in full working condition, and the software is ‘polished/professional’ to ensure as few errors occur as possible, is important to a student’s enjoyment of the subject.

Again, it is important to note that the students were read the questions and asked for their response, at the suggestion of their teacher. This could have influenced what the students said, hiding their true thoughts/feelings.

4.1.5 What were your 5 favourite activities with Comet Chasers?

This question aimed to judge which activities were preferred by the students, in order to understand what aspects or themes best grabbed the students’ attention and interest. Depending on the activity, it would tell us if the students preferred the more traditional science activities, or ones that are more creative in nature.

All of the activities that were conducted are listed in table 4.3 with a brief summary (including topics/concepts taught). Students were asked to select their 5 favourite activities conducted over the 6 interventions.

TABLE 4.3: Favourite Comet Chasers' activities conducted during the 6 weekly interventions. Students were asked to select 5 from the list.

Favourite activity	Summary	n	%
Comet on a stick	<i>Crafts to create a comet nucleus and tail(s) to display how solar winds push back the tails</i>	6	13.3%
Rocket launching	<i>Designing a air-pressure rocket fuselage to be launched outside</i>	6	13.3%
Messier bingo	<i>Bingo game using Messier objects instead of numbers</i>	5	11.1%
Working with NASA on DART Mission	<i>Using LCO network to image Didymos and Dimorphos system to aid NASA's analysis following the DART mission</i>	5	11.1%
Windmill galaxies	<i>Creating paper windmills to explain spiral galaxies</i>	4	8.9%
Creating craters	<i>Throwing rocks at different angles, heights, and speeds into flour to investigate the craters made</i>	3	6.7%
Impact calculator	<i>Web programme which shows the destruction of a variable sized object crashing into custom locations on Earth (often the students' school)</i>	3	6.7%
Rotato	<i>Tabletop experiment using rotating rubber ducks to explain how astronomers create light-curves and why they're useful</i>	3	6.7%
Getting pictures from space	<i>Using LCO's observing portal to request images of any object they wish</i>	3	6.7%
Meteorites and fossils	<i>Handling and investigating real meteorites and fossils</i>	2	4.4%
IR cameras	<i>Investigating how invisible light can be used to measure heat using infra-red cameras</i>	2	4.4%
Quizzes, word-searches, and crosswords	<i>Short, fun paper based activities using astronomy terms</i>	2	4.4%
Researching Messier objects	<i>Internet research based on a selected Messier object and creating a short poster on it</i>	1	2.2%
Total		45	100%

The top 5 activities had > 4 votes each; Comet on a stick, rocket launching, Messier bingo, working with NASA on DART mission, and windmill galaxies (breakdown of votes can be found in table 4.3). Most of these activities were heavily based on the students' creativity, with a lot of time dedicated to designing/assembling.

Comet on a stick, rocket launching, and windmill galaxies were all activities that used students' creativity to produce something they could keep. The fact that these were some of the most popular activities is not surprising as it appeals to even those who are not particularly interested in science, but is used as a vehicle to teach the students about science and astronomy.

Messier bingo's enjoyment comes from the excitement of playing a game. This activity introduces the students to Messier objects (and Messier himself), how these objects were discovered, and how scientists classify differences in astronomical objects. This is an important concept in all scientific fields, as it is often vital to create connections and groups between members within a sample, be that within animals/plants in Biology or astronomical objects in Astronomy.

'Working with NASA' is a natural interest grabber - for all ages. It is interesting that this activity is one of the most popular, but it does not really appeal to students' creativity or innate love of playing. Involving students in real research and associating the work with current/popular topics is effective to nurture interest in the topics - in the short term at the very least. The aim is that this remains as a lingering thought in the students' mind post-intervention.

It is somewhat surprising that 'Meteorites and fossils' had such a low number of votes (2). This activity, from personal experience, usually engages people of all ages the most. Often, students will stop what they are doing to try and find out more about the samples available, and to hold them. Worksheets were distributed and students were asked to complete them by investigating and testing

a sample. This aspect may not be viewed favourably by the students when comparing their enjoyment of the activity with an external perception of their enjoyment. Completing worksheets may be viewed as dull and thus detracted from the interest they may have had initially with the meteorite samples.

Similarly to the ‘Meteorites and fossils’ activity, it was surprising that using IR cameras was also very low on the list of favourite activities. This is one of the most hands-on scientific activities, and gives the students access to real scientific instruments, which they are unlikely to encounter elsewhere. The activity is also based on a worksheet where the students investigate differences in temperature and how light can be used in different ways. A possible explanation could again be that the students at this age do not find value in doing worksheets, even with the exciting and hands-on activity being conducted. Additionally, given that only 3 IR cameras were available for them to use, students may not have had an opportunity to use the camera themselves as they had to share. We encouraged, and sometimes had to enforce, sharing the cameras with all the students, but it could be possible that not all student had an opportunity to lead the investigation, resulting in disappointment and feeling left out.

Note: this questionnaire was completed at the end of 6 weekly interventions, and the activities that occurred later in the series seem to be more popular - this may simply be due to them being more fresh in the students’ minds.

Overall, it is clear that activities involving more creative endeavours are the most popular - this is expected as it would appeal to all children regardless of their interest or ability in science. Another point of view could be that these creative activities remain in the students’ minds more readily, due to the time invested and care taken in creating their comet/rocket/windmill, and keeping the final product. Regardless of which explanation is most true, creative activities for students of this age thoroughly engages them with scientific content (Shanahan and Nieswandt 2009; Susiloningsih et al. 2025).

4.1.6 What did you like most about Comet Chasers?

This question aimed to gather the students' true feelings (in their own words) about the programme as a whole. Responses help guide future workshops to ensure we are able to deliver the aspects most enjoyed by the students to maximise their intrigue for the topics at hand.

Similar to responses in question 3 (section 4.1.3), some students mentioned that the workshops were fun. Note: two of the three that responded 'fun' to this question also said this about science lessons (section 4.1.3).

"Do fun activities and doing rocket, and lots of activities[sic]" (Year 4)

"Extremely fun, amazing, ABSOLUTELY INSANE" (Year 3)

"Way we did everything. Made education extremely fun. Feels didn't learn but did" (Year 3)

Two students enjoyed learning about aspects they would not usually encounter in their normal science lessons.

"Got to learn new things" (Year 4)

"Learning how things work and capacity[sic]" (Year 3)

Meteorite impacts are an exciting topic for young students.

"Impact simulator" (Year 4)

"Finding when a meteorite crash on earth" (Year 3)

This is reinforced given the exciting nature of the impact related activities; students would either use the impact simulator to crash meteors into (usually) their school or home, or throwing rocks and other items into a tray of flour to investigate the craters made.

An interesting response discussed how they liked most the 'social' aspect of the workshops, and being able to interact with professional scientists that work at the university.

"I can socialise with people who go to Cardiff uni" (Year 4)

This reflects a core aspect of the Comet Chasers programme, linking school students with astronomers with the aim of exposing them to the scientific world. It

is valuable to know that the students are aware of this aspect of the programme, as it was assumed that it would not be noted by the participants, although had positive impacts.

4.1.7 What's the most interesting thing you learnt from Comet Chasers?

This question had two primary aims: discover what they found most interesting, and query what the students learnt from the workshops. While enjoyment is prioritised over the students learning facts, it was interesting to see if they are able to recall facts and information from the large amount of content presented to them over 6 weeks. Additionally, this lets us know which aspect of the programme is preferred, allowing us to hone in on that topic to best serve the students in the future.

"How comets work" (Year 4)

"If the meteor is bigger the hole is bigger" (Year 3)

This could be in reference to either the creating craters or the impact simulator activities, which focused on impacts from space.

"How far things can go at different angles" (Year 4)

This response is regarding the creating craters activity which would create large craters when thrown at low angles. This shows that interesting hands-on activities can stay in the minds of young students, especially given this activity was one of the first conducted, well over a month before the questionnaire was completed. The science behind this may not be fully understood by the student, although this is secondary if the curiosity about this remains in the student.

"Messier" (Year 3)

Two activities were focussed on investigating/discussing Messier objects. These activities were more research/learning based than others, which makes it interesting that a young student still finds this topic the most interesting, despite the fact that more hands-on activities were conducted.

Rephrasing this question would have yielded more useful responses. Phrasing it as ‘What facts that you learnt from Comet Chasers would you tell friends/family?’ would encourage more detail and specificity in their responses.

4.1.8 What did you not like about Comet Chasers?

The aim with this question is to find out what activities or aspects of activities the students did not enjoy as much. Knowing what the students do not enjoy is just as important as finding out what they do like, as our aim is to make the workshop as enjoyable as possible.

5 responders noted that they did not dislike anything from the workshops.

“Nothing”

(Year 3s and 4s)

While a positive response (from a Comet Chasers’ point of view), it is not a useful response. There is always room for improvement - especially for such a novel programme such as Comet Chasers. It is clear that there were mistakes made during delivery, leading to possible improvements either in delivery method or the activities themselves.

This is further highlighted as it was one of the first workshops that would be joint-led - due to nerves and inexperience in delivering workshops, naturally, mistakes were made. This response being common is attributed to the students wanting to be ‘nice’ and not being comfortable enough to say their true beliefs. It is of course possible the students could not think of anything they did not like at the time, but safer to assume that the workshop was not perfect, as attributed by some students.

“Loud noises”

(Year 4)

This student had numerous bad reactions to loud noises during activities. Primarily, this occurred during the film canister rocket experiment, which has a loud ‘pop’ when the ‘rocket’ is launched. Despite warning the students of what to expect, we should have been clearer with them and given them the option to leave the classroom if that was something they wished to avoid.

“Lessons were short”

(Year 3)

This piece of ‘criticism’ is very positive, clearly the student would like more Comet Chasers. There is not really an obvious way to solve this feedback, as workshop timings are heavily dependent on the student’s availability and our schedule. In a sense, this point can be viewed as a good sign, as we should follow the old adage, “Always leave them wanting more” - the more intrigue and curiosity we can leave in the minds of the students, the greater their interest and drive to investigate further.

4.1.9 How could we make Comet Chasers better?

This question follows on from the previous question, and responses were expected to be of a similar nature although rephrased. This is aimed at finding out how we can continue to improve the Comet Chasers programme for future interventions.

Two students mentioned that doing more activities could improve the workshops.

“Making more insane stuff”

(Year 3)

“More fun and creative stuff”

(Year 3)

It is very reassuring that students wish for more activities, clearly indicating they enjoyed the workshops. These comments touch on different types of activities: ‘insane stuff’, and ‘creative stuff’.

Presumably, the ‘insane’ activities consist of rocket launching, impact simulator, and creating craters - these activities are conducted due to their ‘wow factor’ and their ability to be appealing to all students. These activities are punchy

and provide an immediate payoff for the students, with thinking about what they did and learnt typically coming after the activity (rather than thinking and planning before/during the activity). As natural ‘attention grabbers’, these particular activities are ideal to draw in initial interest, and convince any students who are on-the-fence about enjoying the workshop.



(A) Comet on a stick activity result.
Credit: NASA (2020)



(B) Galaxy windmill activity result. Credit: NASA (2021)

The more creative activities (comet on a stick (fig. 4.1a), rocket launching, and windmill galaxies (fig. 4.1b)) draw attention from students who may prefer more artistic subjects than science based (STEAM vs STEM, see section 2.2.2 for drawing in creative aspects into STEM to encourage creative solutions and collaboration).

Another student touches on the fact that they would like to do more activities.

“Quicker stuff so that we can do more thingz[sic]” (Year 3)

This is the same student who mentioned that the lessons were short in the previous question (section 4.1.8).

According to one student, the programme is already ‘perfect’.

“Nothing” (Year 4)

4.1.10 How many stars would you give Comet Chasers?

This is a brief summary of their general like/dislike of the programme as a whole. It is a quick and easy way to judge if the interventions were a success or had a beneficial impact on the students.

TABLE 4.4: Summary of stars given to the Comet Chasers programme from the initial trial school.

Method	Value
Weighted average	4.78
Median	5
Mode	5
NPS	100%

2 students gave 4 stars, while the remaining 7 gave 5 stars, giving a weighted average of 4.8.

4.1.11 Would you like to carry on doing Comet Chasers with [teacher]?

All but one student responded that they would like to continue Comet Chasers with their teacher. Note: the student who said ‘No’ did specify that was due to them changing class in the next school year and therefore having a different teacher - different from the one specified in the question.

4.2 Reflection

This series of weekly workshops was a beneficial way to test out the existing Comet Chasers’ material on a longer-term basis, while also honing a personal delivery style and confidence in front of a class. The students were all very friendly and eager to learn and interact with the programme, making teaching easier - a gift for a novice presenter!

The main lesson learnt was to prepare well in advance if any ethical approval needs to be authorised. Waiting for ethical approval was the main source of anxiety, concerned that it would take longer to be approved than the interventions lasted and result in no evaluation data being obtained. Thankfully, approval was granted before the final workshop, and thus the post-engagement questionnaire could be completed. Weekly questionnaires would have been beneficial to gain a better insight into the students' opinions on individual activities.

The delivery of these workshops contributed to the development of confidence in leading classroom-based teaching. Prior to this experience, involvement in similar activities had been limited to occasional participation in public 'table display' events or assisting other presenters. Transitioning from a supporting role to a leading role introduced additional challenges, particularly in the preparation and structuring of lesson plans. Although supporting resources were available, significant preparation was required during the week preceding each session, with particular emphasis on practising the workshop introduction to ensure it was engaging, informative, and accessible to the intended audience. Consistent interaction with the same group of students on a weekly basis further supported the development of confidence, as familiarity with the audience reduced uncertainty regarding participant responses and engagement with the activities.

These workshops helped to hone delivery style, helping enormously in later interventions. Initial plans were formed for the 'standard' workshop for solo-delivery, while drawing further insights from other activities.

As the students (years 3 and 4) were younger than the material was initially designed for (years 5 and 6), it was a good way to check if the material was explained clearly. More care and attention had to be given to make sure the students truly understood the activities. Conducting to a younger audience evoked certain questions due to a lack of clarity, or assumptions as to what they already knew. This resulted in the refinement of the content presented ensuring that the questions would not need to be asked by future students.



FIGURE 4.2: Photo cleaning up the classroom following the students making their own comets on sticks.

Another benefit of presenting to younger years was that it ensured that students of lower ability in older years could be involved. This is such an important point for the programme, given the main focus being enjoyment and interest in the workshops, rather than just learning. Ensuring that the youngest students can interact and gain value from the workshops is crucial to the programme's success - the aim is to encourage and intrigue students, but if only those who already enjoy science gain value, what is the point?

Following the completion of the post-evaluation questionnaires, the questionnaires were modified to be clearer and to return more applicable and useful responses. Naturally, post-evaluation assessment needs to be adapted for each workshop as the contents may vary. Despite this, a template was formed from lessons learnt regarding this questionnaire. For this purpose, it was especially useful to treat this questionnaire as a one-to-one focus group, as it could be directly assessed if some questions were not phrased in the best way or led them towards confusing conclusions. Adaptions were made to accommodate these issues.

Finally, these workshops highlighted the time requirements for set-up/clean-up

for the sessions. Often, we would rush to get all the equipment ready shortly before the session began. Thankfully, the schedule was generally clear following workshops, meaning clear up was not time-limited. Learning how much time was needed for the setup and clear-up was crucial for future cases where other workshops were organised shortly afterwards, ample time was allocated for setting up and packing away.

Chapter 5

Outreach Events

Several Comet Chasers’ interventions were organised, primarily in 2 one-week periods, one in June 2023 and the other in February 2024. Additional one-off workshops occurred around this period. For the June 2023 and February 2024 interventions, I worked with See Science to organise interventions at 10 schools in north west Wales. All schools visited and their demographics are displayed in table [5.1](#).

Total number of students in schools visited varied from 25 to 265 students during the 2022/23 academic year. Most schools fell below the local authority’s average percentage of students eligible for free school meals, with three exceeding both regional and national averages (Ysgol Santes Dwynwen Ysgol Gymuned Llanfechell, Capcoch Primary School). [Welsh Index of Multiple Deprivation \(WIMD\)](#) scores vary significantly considering all schools are located in two nearby counties. The average number of students in Ynys Môn and Gwynedd are far smaller than those in Cardiff, with the smallest Cardiff primary school having 90 students (Welsh Government [2025b](#)). Given smaller schools, the budget per pupil is on average £500 more for rural schools, while the teachers per pupil ratio remains consistent.

Students were mainly in Year 5 although some classes included students in years 4 and 6. Each class had typically 25 students. Comet Chasers' workshops lasting ~ 90 min were scheduled with each school. The session itself would last an hour, with an additional ~ 15 min reserved before and after the activities for set-up and tidying away.

TABLE 5.1: Table summarising demographics of schools visited as part of the Comet Chasers programme. Data is obtained from Welsh Government (2025a) and Welsh Government (2019), and is for the 2022/23 academic year unless stated otherwise. ¹Free School Meals. ²Pupil to Teacher Ratio. ³Budget per pupil. ⁴Welsh Index of Multiple Deprivation ranking from 2019 (1 is most deprived, 1909 is least deprived). For context, average values for Ynys Môn, Gwynedd, and Cardiff are listed, along with national values where appropriate.

School	County	# Pupils	FSM ¹ (%)	PTR ²	B/P ³ (£)	WIMD ⁴
Ysgol Gynradd Llanfairpwll	Ynys Môn	265	2.2	23.6	3,763	1,704
Ysgol Llanllechid	Gwynedd	205	9.3	22.5	3,939	957
Ysgol y Gelli	Gwynedd	170	4.6	22.0	3,805	1,454
Ysgol Eifion Wyn	Gwynedd	160	7.6	22.2	4,112	1,661
Capcoch Primary School	RCT	150	35.0	29.0	3,672	245
Ysgol Bro Llifon	Gwynedd	125	9.4	21.4	4,293	1,375
Ysgol Cefn Coch	Gwynedd	120	6.9	19.1	4,489	1,338
Ysgol Bethel	Gwynedd	120	6.3	21.7	4,053	1,606
Ysgol Henblas	Ynys Môn	75	8.9	22.3	4,931	1,036
Ysgol Parc y Bont	Ynys Môn	90	6.5	22.2	5,028	954
Ysgol Santes Dwynwen	Ynys Môn	85	23.8	14.4	5,259	764
Ysgol Gymuned Llanfechell	Ynys Môn	65	30.4	21.1	4,911	864
Ysgol Talsarnau	Gwynedd	25	13.0	14.8	5,760	1,254
Ynys Môn Average		114	17.5	20.5	4,507	
Gwynedd Average		87	14.6	18.8	4,509	
Cardiff Average		256	27.7	20.8	3,995	
Wales Average		167	23.0	21.0		

Due to the number of schools being visited in a short period of time, a structured plan needed to be applied for all schools. This meant that preparing for each individual school was much easier and not as much additional preparation was needed between sessions (other than minor amendments from ‘lessons learnt’ from previous workshops). Having a structured workshop was also beneficial given that I was presenting them alone. It allowed me to be prepared for issues or questions that might arise, with the students’ behaviour and willingness to learn being the major variables.

Sessions would begin with a short presentation on the basics of comets (structure, origin, activity). This presentation included animations to visually explain the concepts, while asking the students questions to make it less static and one-sided.

Often, this presentation was paired with the Rotato experiment already running and clearly visible to the class. A large plush penguin was rotating on the turntable to increase curiosity, see fig. 2.11a. This ‘visual draw’ was also used during outreach events to attract visitors to the Comet Chasers display - people were intrigued to know why we had a spinning penguin and what it had to do with space. This method of drawing the students’ attention, while seemingly counter-intuitive, leads the students to ask more questions (both to myself and each other), and sometimes acted as a non-verbal icebreaker.

Following the presentation and explanation of the two activities the students would take part in, including a quick demonstration of the Rotato experiment, I intentionally tried not to explain everything in great detail. I aimed to assess how the students would conduct the activity and respond to using the worksheets, also to see how their intuition would figure things out for themselves. Worksheets for the Rotato experiment were created based on those made for the ‘Exoplanet Hunters’ outreach programme. The ‘IR camera’ worksheets were also translated from pre-existing resources. Additional documents were supplied, providing details regarding the functions of the Rotato software along with basic hints for what to investigate (see appendix B).

Students were separated into two groups, one for the Rotato experiment, and one using [IR](#) cameras. After ~ 20 minutes, the groups swapped to ensure they all had an opportunity to complete both activities.

During the first few sessions, I introduced meteorite samples as part of the initial presentation, passing them around and asking what they thought they were. Two large meteorite samples were used, one stony (chondrite) meteorite and one iron meteorite. These had an obvious difference in density, and the difference in their weights would often surprise those who held them. I quickly noticed that they would occasionally act as a hindrance from the activities as it drew attention away from the students' tasks. To remedy this, I would use the samples as a motivator when groups started to chat and seem to lose interest in the work. When I noticed a group of students not fully engaging with the activities, I showed them the meteorites and asked them questions about them, e.g. "What do you think they are?", "What do you notice comparing them both?", "Why do you think they are different?" Letting the students hold the meteorites and then explaining their origin, rarity, and age would always peak their interest, even for those who did not initially engage with the activities. They then had the opportunity to discuss with their peers and use the samples in their current activity.

The two activities were the Rotato experiment and using [IR](#) cameras. Both activities aim to explain how astronomers are able to investigate and analyse far away objects using different techniques.

Rotato: The Rotato is a tabletop experiment to explain how lightcurves of objects in space can be produced, and what they can tell us. An object is placed on a turntable - this represents the comet nucleus/asteroid in space. A torch (the Sun) and webcam (the telescope) are aimed at the object with the intensity of the reflected light from the torch into the camera measured using software written by myself, [fig. 2.11a](#). In real-time, the user can compare the video feed from the camera with the lightcurve being plotted, [fig. 2.11b](#). This experiment

shows clearly how small changes in the reflected light can be used to deduce numerous parameters of the object, including its shape, colour, and size. Further explanation of the Rotato experiment can be found in section 2.4.1.3.

IR cameras: The IR camera activity explained how different wavelengths of light (often invisible to us) can be used to discern the temperature of an object. Handheld (FLIR C5) IR cameras were given to students, and they were allowed to investigate the temperatures of objects in the classroom. Some pre-prepared activities were used to guide the students towards understanding the concept of measuring temperature without any contact. Two identical bottles were filled with water, one with cold water and the other with hot water. Initially using only their eyes, it was impossible to tell which bottle contained the hot water (apart from eagle-eyed students who spotted some condensation inside the hot bottle) - by using the IR camera, it becomes easily apparent which bottle was hot and which was cold. Another activity involves looking at body temperature and how clothes, hair, and glasses all have an effect on the heat emitted from the body. Students would always enjoy and be intrigued by pressing their hand against a surface and seeing a 'remnant' handprint, from their body heat, through the camera (which is invisible to the eye). The group was also tasked with finding hidden objects (battery-powered hand warmers) in the classroom. Visually they would be covered with something like paper or fabric, or placed behind an object, while the IR camera would easily reveal them. A 'spanner in the works' for the students would be a hand warmer hidden under a Mylar foil blanket, which blocks the IR light emitted.

5.1 Evaluation Received

While pre and post-engagement questionnaires were distributed to each school that attended, inevitably not all completed them. 7 schools completed the pre-engagement survey, with 5 of those also completing the post-engagement survey.

TABLE 5.2: Summary of schools visited, date visited, estimated class size, and whether they completed the pre and post-engagement questionnaires. Note: schools were grouped either by the school name supplied in the questionnaire, or by the start data of the questionnaire. Responses that began at the same time come from the same school.

School	Date visited	Class size	Pre-engagement	Post-engagement
A	06/06/2023	30	Y	N
B	07/06/2023	30	Y	N
C	08/06/2023	20	Y	Y
D	08/06/2023	25	N	Y
E	09/06/2023	18	N	Y
F	12/06/2023	18	Y	N
G	12/06/2023	20	N	Y
H	27/11/2024	25	Y	Y
I	10/07/2025	2x25	Y	N
J	??	??	Y	??

I am unaware as to which school, specifically, school J is, as all students responded ' [PNTA](#)' to this question. Due to the proximity of the start time/date of these responses, it is clear they are from the same school, and definitely separate from the other schools who did provide a school name. It is therefore not possible to provide the date visited or class size of this school. Additionally, it is possible that the post-engagement questionnaire was completed by this school, although it would be impossible to tell. For the purposes of this study, school J is considered separately and different from any other school that completed the questionnaire.

5.2 Pre-Engagement Evaluation

These questionnaires aimed to assess the students' science capital - specifically their attitudes towards, experiences with, and knowledge of [STEM](#) subjects, and well as their perceptions of how these subjects are used in the adult world. The questionnaire included basic demographic queries (e.g. school year and school attended), along with questions about students' enjoyment of science lessons and whether they have relatives working in [STEM](#) fields.

Science capital has been found to have significant influence on a students' desire to pursue [STEM](#) post-16 (Archer Ker et al. [2013](#)). Students from families with high science capital are more likely to aim for careers in [STEM](#), Archer et al. ([2023](#)) notes that those from lower science capital families are more reliant on chance to be exposed to experiences to build science capital. Exposure of students to role models from backgrounds and identities similar to their own can also encourage uptake of [STEM](#) careers later in life (Gladstone and Cimpian [2021](#)). Pupils from under-represented groups (i.e. not white, middle-class males) are less likely to pursue [STEM](#) jobs because they don't identify with the field due to the lack of representation, therefore these are important groups to encourage into [STEM](#) (Archer Ker et al. [2013](#)).

Of the approximately 350 students invited to complete the pre-engagement survey, 154 responded, yielding a response rate of around 44%. These responses came from seven different schools, schools A, B, C, F, H, I, J.

All questions were originally written in Welsh with English translations provided. In this document, translated questions are presented alongside the original Welsh text in brackets.

It is important to note that the questionnaire was administered under both the opt-in and opt-out systems. Students were required to complete the questionnaire themselves, and any responses which were clearly completed by a parent (pre consent method change) or teacher were excluded. One parent completed the questionnaire, stating in numerous questions that it was a parent completing the questionnaire, therefore this response was excluded from the analysis as it did not meet the participant criteria.

5.2.1 Respondent Demographics

What school year are you in?

Pa blwyddyn ysgol wyt ti mewn?

TABLE 5.3: Distribution of student respondents by school year in the pre-engagement questionnaire. Most responses came from Year 5 students, with smaller proportions from Years 4 and 6. A small number of students chose not to disclose their year group.

School Year	n	(%)
Year 4	36	(23%)
Year 5	66	(43%)
Year 6	43	(28%)
PNTA	9	(6%)
Total	154	(100%)

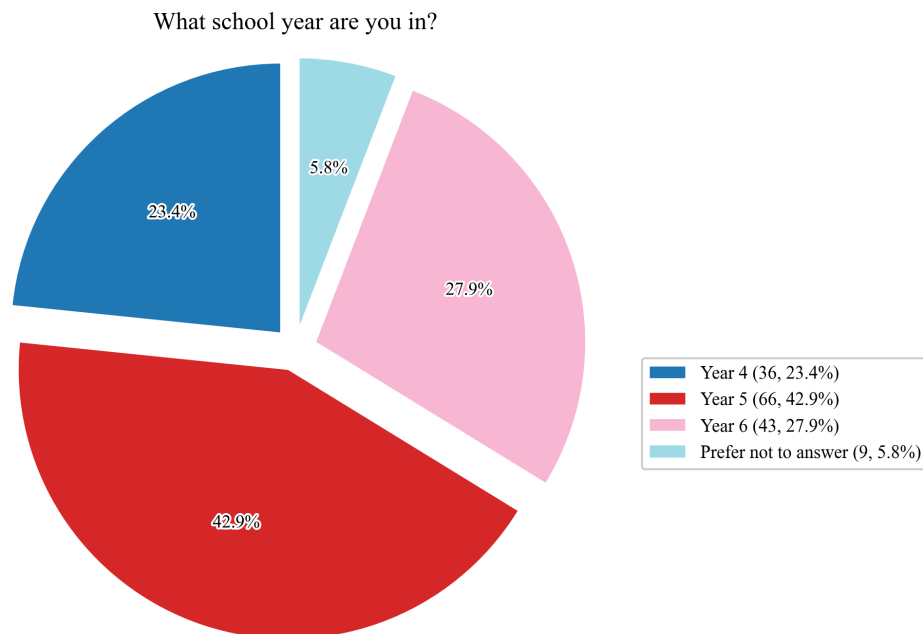


FIGURE 5.1: Pie chart showing the distribution of school years among students who participated in the pre-engagement survey (N=154). Year 5 students represented the largest group of respondents.

Comet Chasers' workshops were primarily offered to students in Years 5 and 6. Some schools requested that Year 4 students also be included, with one school consisting primarily of students in Year 4. Although the resources are suitable for Year 4 students, delivering the workshops to this age group could be more challenging — particularly when conducting a workshop by myself.

It is essential that students across all targeted year groups — and of varying abilities — are able to derive value from the workshops.

TABLE 5.4: Distribution of student year groups by school for the pre-engagement questionnaire. Percentages in brackets indicate the proportion of each year group within that school. The ‘Total’ column shows each school’s contribution to the overall sample.

School	Year 4		Year 5		Year 6		PNTA		Total	
A	0	(0%)	8	(35%)	14	(61%)	1	(4%)	23	(15%)
B	0	(0%)	19	(100%)	0	(0%)	0	(0%)	19	(12%)
C	0	(0%)	11	(44%)	14	(56%)	0	(0%)	25	(16%)
F	0	(0%)	13	(100%)	0	(0%)	0	(0%)	13	(8%)
H	14	(64%)	0	(0%)	0	(0%)	8	(36%)	22	(14%)
I	16	(36%)	13	(30%)	15	(34%)	0	(0%)	44	(29%)
J	6	(75%)	2	(25%)	0	(0%)	0	(0%)	8	(5%)
Total	36	(23%)	66	(43%)	43	(28%)	9	(6%)	154	(100%)

The majority of students who responded were in Years 5 and 6, which aligns with the target audience for the Comet Chasers’ workshops. As such, their responses are particularly relevant to the programme’s objectives. Although fewer in number, the responses from Year 4 students offer valuable insight into how younger pupils engage with [STEM](#) and perceive their science capital.

What school do you go to?

Pa ysgol wyt ti’n mynd i?

Seven of the twelve schools invited to complete the pre-engagement questionnaire provided responses. School I submitted the highest number of responses, followed closely by Schools D, B and F. Schools C and F appeared to consist of single-year classes, while the remaining schools included mixed-year groups. However, due to several ‘[PNTA](#)’ responses, it is not possible to confirm this definitively for School F.

Tab. [5.4](#) presents the distribution of student year groups for each school that responded to the pre-engagement questionnaire. Percentages in the year columns indicate the proportion of students from each year within that school, while the percentages in the ‘Total’ column reflect each school’s contribution to the overall sample.

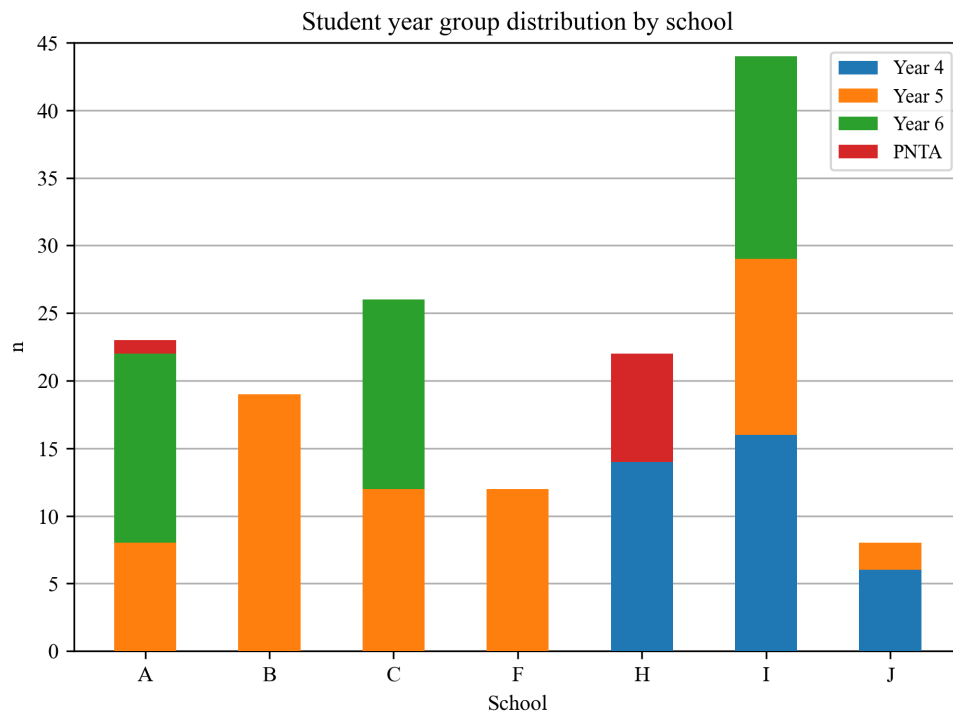


FIGURE 5.2: Breakdown of student year groups by school for respondents to the pre-engagement survey. This figure highlights the variation in year group composition across participating schools (N=154).

5.2.2 Desired Job

What sort of job do you want when you grow up?

Pa fath o swydd wyt ti eisiau pan ti'n tyfu i fyny?

This question aimed to explore students' interest in pursuing [STEM](#)-related careers in the future. As an open question, students were free to write any career they aspired to. Given the wide variation in responses, careers were grouped into thematic categories for analysis. The most common categories included: [STEM](#), art, healthcare, hospitality, police, sport, education, and other. Tab. [5.5](#) presents a breakdown of students' career aspirations by year group. Numerous jobs fall into different categories, for example 'Doctor' would be considered a [STEM](#) and healthcare job. These are included, therefore the total count in tab. [5.5](#) does not sum to the total number of responders.

Naturally, it is not expected that students will ultimately pursue the exact careers listed. Rather, their responses provide insight into their current awareness

of career options and how these may relate to their interests and favourite school subjects¹. It is more of an indication of students' awareness of careers available and to see if they relate to their favourite subjects/topics in school. See sect. 5.2.4 for relation to students' desired job and favourite subject.

The most frequently selected career type was [STEM](#), with 34 responses (22%) being a [STEM](#) job. [STEM](#) jobs are fairly popular in literature, with 35% of respondents in the Aspire survey indicated that they would like a job that 'uses science' (Archer Ker et al. 2013). Archer Ker et al. (2013) found that although only 15-17% (dependent on age) of students aim to be a Scientist, careers in Engineering and Medicine are more popular.

The second most frequently mentioned career category was sport, with 30 responses (19% of total). This is unsurprising, as students often idolise sports' figures or are influenced by their extracurricular involvement in sporting activities. While most sport-related responses were for roles such as football or rugby players, one student notably expressed an interest in becoming a physiotherapist for footballers — demonstrating an awareness of alternative careers linked to the sports' industry. Due to the nature of this job, it was included in categories sport, [STEM](#), and healthcare.

¹As a personal reflection, I recall listing 'Magician', 'Astronaut', and 'Welsh rugby player' in similar surveys during my own school years.

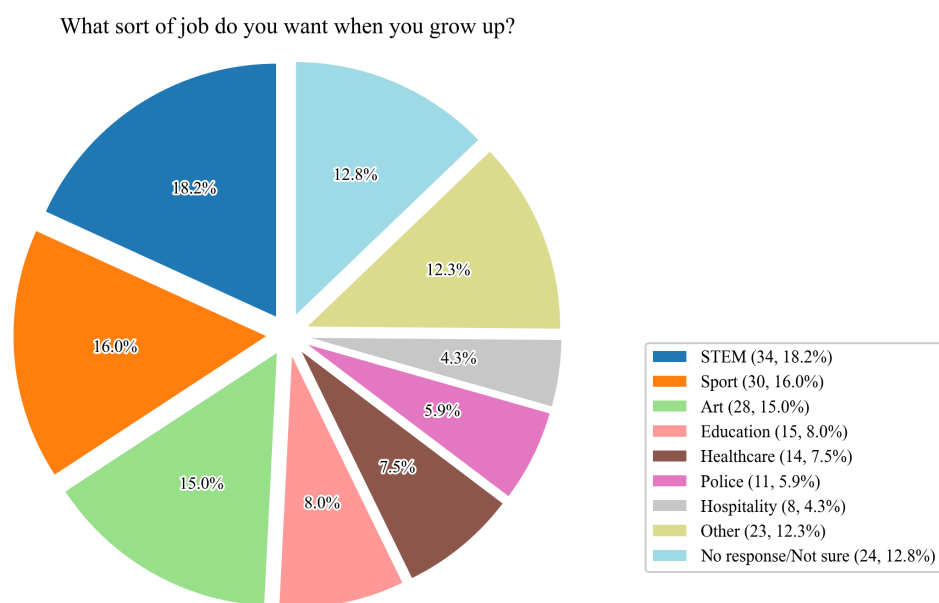


FIGURE 5.3: Distribution of students' career aspirations by category (N=172). Categories were created to group similar responses and account for variation in how students described their desired careers.

TABLE 5.5: Career aspirations of students from the pre-engagement survey (Question 3), grouped by thematic category and year group. Percentages in the year columns represent the proportion of responses for each year group, while the ‘Total’ column shows each category’s share of all responses. Some students listed multiple careers.

Career Type	Year 4	Year 5	Year 6	PNTA	Total	Examples
STEM	6 (17%)	14 (21%)	11 (26%)	3 (33%)	34 (22%)	Astronaut (Year 5, school A), vet (‘Milfeddyg’, Year 5, school F), Engineer (Year 5, school B), scientist (‘Gwyddonydd’, Year 5, school A)
Sport	5 (14%)	17 (36%)	8 (19%)	0 (0%)	30 (19%)	F1 driver (Year 6, school A), football player (‘pêl-droediwr’, Year 5, school C), Rugby player (Year 5, school C)
Art	5 (14%)	14 (21%)	13 (30%)	0 (0%)	28 (18%)	Musician (‘Cerddor’, Year 5, school B), Author (Year 6, school C), Interior design (Year 6, school A), Actor (Year 5, school A)
Education	4 (11%)	8 (12%)	2 (5%)	1 (11%)	15 (10%)	Teacher (‘Athrawes’, Year 5, school B), primary school teacher (‘Athrawes ysgol gynradd’, Year 5, school C)
Healthcare	3 (8%)	6 (10%)	4 (9%)	1 (11%)	14 (9%)	Nurse (‘Nyrs’, Year 5, school F), child care (‘Gofal plant’, Year 5, school F), Doctor (Year 6, school A)
Police	3 (8%)	4 (7%)	2 (5%)	0 (0%)	9 (6%)	‘cop’ (Year 4, school I), ‘S.W.A.T’ (Year 5, school B), police (‘Heddlu’, Year 5, school F)
Hospitality	2 (6%)	5 (8%)	1 (2%)	0 (0%)	8 (5%)	Chef (‘cogydd’, Year 5, school B), ‘flight attendant’ (Year 6, school I)
Other	5 (14%)	5 (8%)	6 (14%)	0 (0%)	16 (10%)	Army (Year 5, school B), Groundwork (Year 5, school I), Farming (‘Ffermio’, Year 5, school F), Retail (‘Gweithio [sic] yn Huws Gray’, Year 6, school C), Entrepreneur (‘ontrupynor [sic]’, Year 6, school A)
Not Sure/Illegible	7 (19%)	3 (5%)	3 (7%)	5 (55%)	18 (12%)	–

TABLE 5.6: Table showing students' responses about knowing a science professional.

Know someone in STEM?	n	(%)
Yes	25	(16%)
No	62	(40%)
Not sure	67	(44%)
Total	154	(100%)

5.2.3 Personal Connections to Scientists

Do you know someone who works in science?

(Wyt ti'n adnabod rhywun sydd yn gweithio yn gwyddoniaeth?)

This question served a dual purpose: to determine whether students had close family members or family friends/associates working in a STEM field, and to assess the pupils' awareness of what constitutes a STEM-related job. The hypothesis was that students in more rural areas — such as north-west Wales — would be less likely to know someone employed in a STEM-related profession and would have lower awareness of what constitutes a STEM job, compared to students in more urban settings. This assumption is based on the differing industries and career opportunities typically available in rural versus urban areas, which may limit students' exposure to certain professions.

It was also hypothesised that students with family members working in STEM would be more inclined to pursue STEM careers themselves or express greater enjoyment of science lessons, due to increased exposure and familiarity with such professions. This trend has been supported by previous studies Siregar and Rosli (2021) and Stefani (2024), which also highlight the significant influence of gender — both of the parent working in STEM and of the child — on future career aspirations and perceptions.

Overall, 25 (16%) said they did know someone who worked in science, with 62 (40%) saying they did not, and 67 (44%) saying they were not sure. Only 5 students (20%) of those who said they did know someone in science wished for a

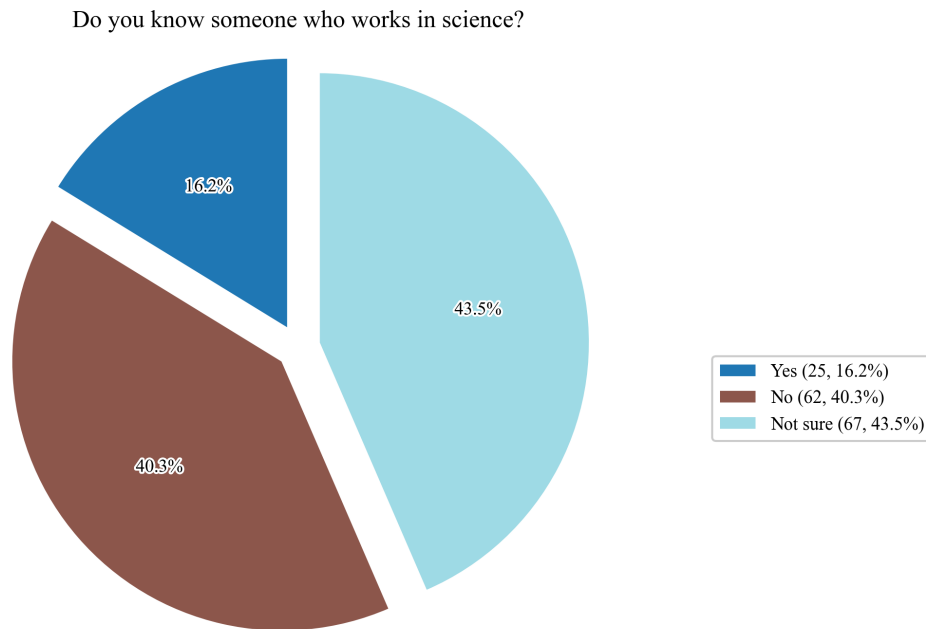


FIGURE 5.4: Chart showing if students know someone who works in a STEM related field (N=154).

job in STEM. Of those who did not know someone working in science, or were not sure, 29 (22%) opted for a STEM job. While the data suggest that students who don't know someone working in STEM are slightly more likely to express interest in a STEM career, the small sample size — particularly among those who answered “yes” — limits the strength of any conclusions drawn from this finding. This is not in line with findings by Archer Ker et al. (2013), who found that students from families with high science capital are more likely to pursue STEM post-16.

Given the low proportion of students who reported knowing someone working in a STEM-related field, this finding reinforces the importance of Comet Chasers' aim to connect students with ‘real scientists’ (astronomers in this case). Role models from similar backgrounds and demographics increase a student's interest and self-belief in STEM (Appel et al. 2021; Shin et al. 2016), while also displaying a career in STEM is achievable (Gladstone and Cimpian 2021) These interactions would help expand students' horizons, giving a deeper knowledge

TABLE 5.7: Student responses to the question: “Do you know someone who works in a STEM-related field?” Responses are grouped by answer type, with corresponding counts and percentages.

Relation in STEM	n	(%)
Family friend	9	(32%)
Other family member (Grandparent, Aunt/Uncle, Cousin)	7	(25%)
Parent/Guardian	4	(14%)
Sibling	4	(14%)
PNTA	4	(14%)
Total	28	(100%)

into not only the astronomy taught, but how the world of science works, highlighting collaboration, research, and experimenting - aspects that may not be touched on in traditional science lessons. Not only would students get to know scientists, but the programme would enhance their science capital by informing them about jobs in the field, and introduce potential role models to those who may be under-represented in STEM fields, giving a richer view into the world of science.

For students who did know someone who worked in a STEM job, it is useful to know what their relation with them is.

Who do you know that works in science?

(Pwy wyt ti'n gwybod sydd yn gweithio mewn gwyddoniaeth?)

From the 25 who said they did know someone working in STEM, 21 specified the relation. Tab. 5.7 shows the breakdown of the relations. Note, some students listed numerous relations who work in STEM, hence, total values will not equal those who said they did know someone who worked in STEM.

There is a fairly even spread of the relative type of those who work in STEM, albeit a small sample. While ‘family friend’ is the largest group, this is expected as students will likely have more family friends than they do parents or siblings.

Interestingly, ‘parent/guardian’ and ‘sibling’ are the smallest groups for relation in STEM. This could be explained by the fact that students will usually have

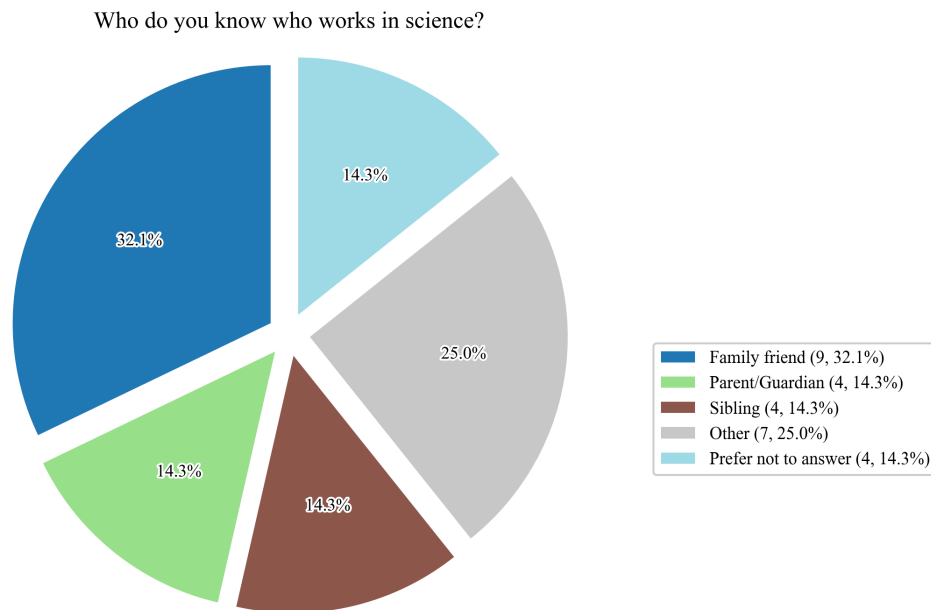


FIGURE 5.5: Distribution of student responses regarding whether they know someone employed in a STEM-related profession (N=28). This question aimed to assess both exposure to STEM careers and awareness of such roles.

fewer of these relations and more in the other groups, leading to a natural difference in the number of responses. Due to the relation working in STEM most likely not being one of the students' parents, it is understandable why there is a low proportion of students who know someone in the field and opted for a job in STEM. A role model figure for a job in STEM would not have such a strong bearing on the students' opinions of science compared to the influence by a parental figure. This may be why there is not a large increase in students who opt for a job in STEM between those who do know someone in STEM, and those who do not - there might be some influence from other family members, but it is not overwhelming.

Again, the sample size for those who do know someone in a STEM field is quite small, so any conclusions cannot be conclusive.

5.2.4 Favourite Subject

What's your favourite subject in school?

TABLE 5.8: Table showing students' favourite subject in school. Some responses consisted of numerous subjects, thus the total does not equal the number of responses.

Favourite subject(s)	n	(%)
Arts and Humanities	69	(43%)
<i>Art (Painting, music, drawing)</i>	44	(27%)
<i>History</i>	11	(7%)
<i>English</i>	8	(5%)
<i>Welsh</i>	5	(3%)
<i>Geography</i>	1	(1%)
STEM	61	(38%)
<i>Maths</i>	38	(23%)
<i>Science</i>	12	(7%)
<i>ICT</i>	11	(7%)
Physical Education	31	(19%)
PNTA	2	(1%)
Total	162	(100%)

(Beth ydi dy hoff pwnc yn ysgol?)

Students were asked to select their favourite subject in school. Although the question requested a single response, numerous students listed two or more subjects. These multi-subject responses were included in the analysis, which is why the total number of subject selections exceeds the number of respondents. Illegible responses were excluded from the dataset.

Art was the most frequently selected subject, accounting for 27% of all responses, suggesting a strong overall preference for creative disciplines. Maths followed as the second most popular subject, with 23% of responses.

When grouped into broader categories — Arts and Humanities versus **STEM** — the responses were relatively balanced, with 43% favouring a subject within Arts and Humanities and 38% favouring a **STEM** subject. These proportions are similar to what is seen by Murphy et al. (2013), with 39% preferring Arts and Humanities and 34% preferring **STEM**. Murphy et al. (2013) has similar proportions with respect to PE (22%).

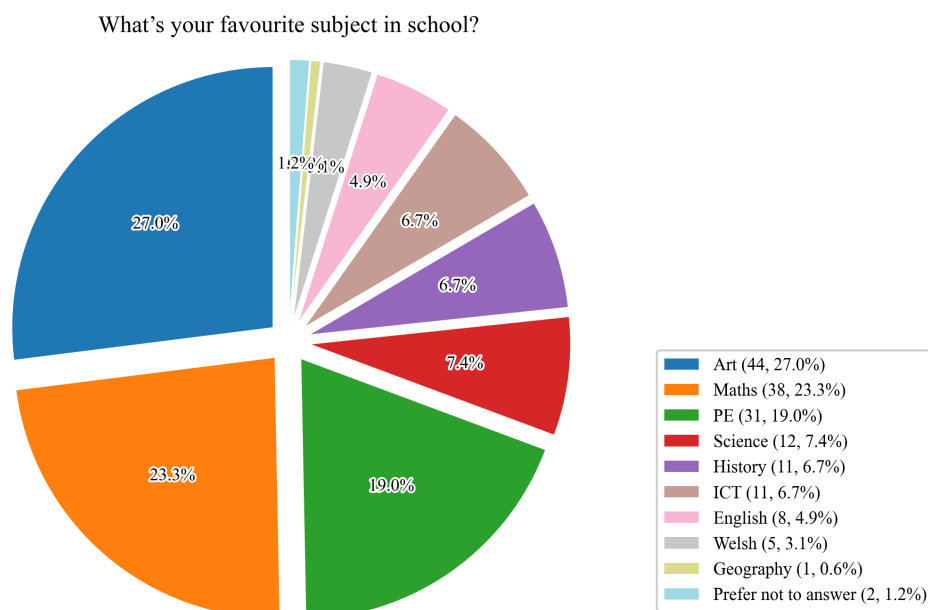


FIGURE 5.6: Responders' favourite subject in school (N=162).

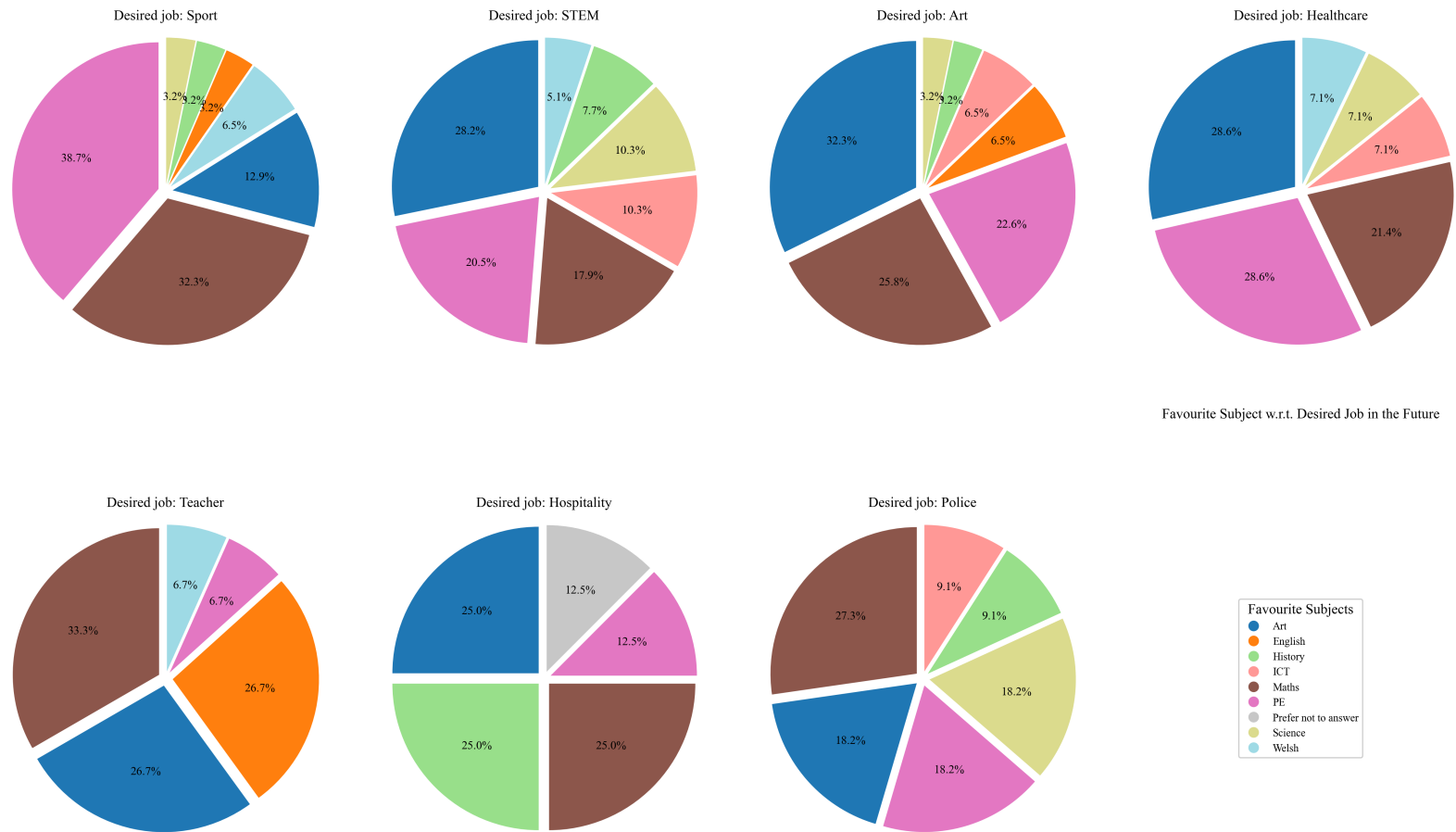


FIGURE 5.7: Distribution of respondents' favourite subject based on their responses to their desired job (N=162).

From fig. 5.7, it is clear that students' desired career is not always related to their favourite subject in school. This is best seen in the second subplot, [STEM](#), where Science is the fifth favourite subject, with Maths and ICT being the 3rd and 4th most popular, respectively. The most popular subject for those who wish for a job in [STEM](#) is Art, followed by PE, and then Maths - this is incongruent with the expectation that those who desire a job in [STEM](#) would enjoy [STEM](#) subjects the most. By combining Science, Maths, and ICT into a [STEM](#) subject, this would overtake the number of students who selected Art as their favourite subject for those who desired a [STEM](#) job. This highlights that more must be done to ensure that students are aware of how subjects are able to be applied in the real world, or not enough is done to help students to realise that certain jobs involve [STEM](#) subject. For example, students may have chosen a job while unaware it is considered a [STEM](#) field, resulting in this discrepancy between desired job and favourite subject. This inconsistency is somewhat limited to [STEM](#) jobs, and other job fields do not have direct subject(s) associated (such as Hospitality, Police, and Healthcare); some fields require a broader range of subjects (such as Teaching), or some fields do match with the students' favourite subject (such as Art and Sport).

Art, as a favourite subject, dominates each field, other than for Sport, Education, and Police. This highlights the broad appeal that Art has as a subject. For Comet Chasers' purposes, it is important to include creative aspects in the workshops to appeal to not only those who enjoy [STEM](#) subjects. This is reinforced by the recent shift from using the term [STEM](#) to STEAM, to include Art, and studies which highlight the importance of creative activities to engage students in science (Shanahan and Nieswandt 2009; Susiloningsih et al. 2025).

This contrast between subject preference and career aspiration may suggest that students are not fully aware of the academic pathways associated with different professions, especially for [STEM](#) jobs. Alternatively, students may enjoy certain subjects without understanding the range of careers those subjects can lead to. This highlights the need for stronger connections between classroom learning and real-world applications in career education. Comparing this data with

responses from students in secondary school could provide insight into how these perceptions evolve throughout a student's educational journey. Comet Chasers aims to address this by discussing different careers available in science, not only as a scientist but those supporting them to ensure that high-quality science can be conducted. Further awareness of what a [STEM](#) job can be is required and could lead to further engagement in [STEM](#) subjects in the classroom.

5.2.5 Science Lesson Enjoyment

Do you enjoy science lessons?

(Wyt ti'n mwynhau gwersi gwyddoiaeth?)

Assessing students' enjoyment of science lessons is a key component of this study, as their engagement with the Comet Chasers' workshops serves as the primary indicator of the programme's success. Students' attitudes toward science lessons in school provide a useful baseline for evaluating the impact of the programme. If students report high enjoyment of the programme, despite a broad range of attitudes toward regular science lessons, this would suggest that the programme successfully engages a wide spectrum of learners — not just those already inclined toward science.

A majority of students rated their enjoyment of science lessons as 4 or 5 (57.9%), indicating a generally positive attitude toward the subject. While this is a promising result for the study, it may not be fully representative of the broader student population. It is possible that students were selected to participate in the workshop based on their existing interest in science. While many schools visited were small enough to conduct workshops with a whole year group, it was naturally not possible for all schools. Teachers were responsible for selecting students to take part in the workshops - this could be by a whole class, or a selected subset of those who enjoy science lessons the most. It was requested that pre-engagement questionnaires were distributed to all students in any given year(s), although this was not carried out in all schools. Additionally, students'

TABLE 5.9: Summary of the ranking of how students enjoy science lessons in school. 1 means that students do not like science at all, and 5 means that they love them.

Ranking	n	(%)
1	5	(3.3%)
2	14	(9.2%)
3	45	(29.6%)
4	41	(27.0%)
5	47	(30.9%)
Total	152	(100%)
Weighted average		3.73
Median		4
Mode		5
NPS		45.4%

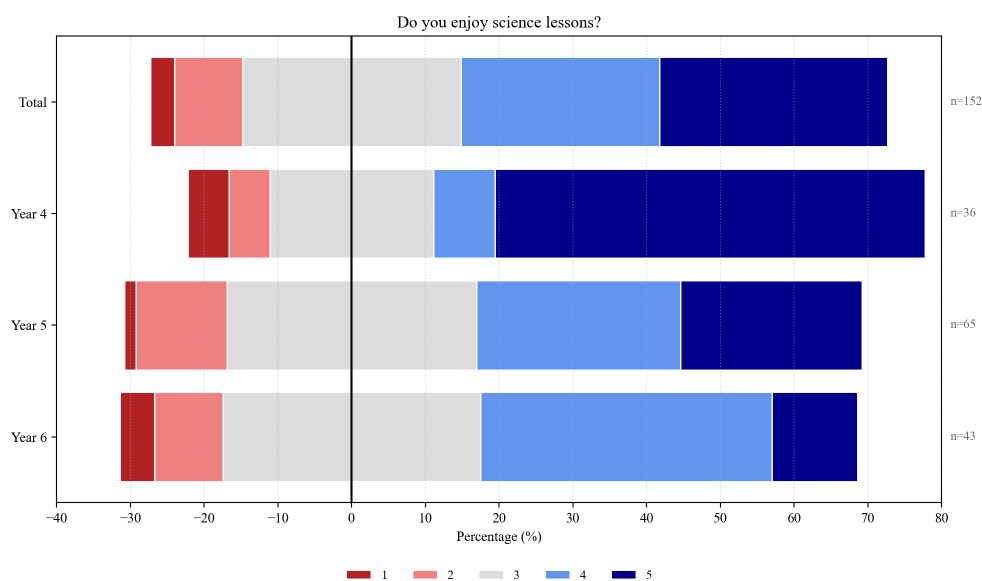


FIGURE 5.8: Responses to question 7: Do you enjoy science lessons? Where 1 is ‘not at all’ and 5 is ‘love them’. Breakdown of year group’s opinions are displayed (N=152). Students who opted not to answer were not counted.

enjoyment of science will be influenced by their teacher's enthusiasm for the subject. This introduces bias, as teachers who are passionate about science may be more likely to seek out enrichment opportunities such as the Comet Chasers' workshops.

Fig. 5.8 shows the trend that enjoyment of science decreases as students age, with fewer students ranking their enjoyment of science lessons a 4 or 5 between Year 4 and Year 6. This is congruent with findings by Pell and Jarvis (2001) and Murphy and Beggs (2003), who also found decrease in interest, despite confidence in their ability increases.

Targeting students at a young age gives the best opportunity to engage and enthuse them in STEM subjects, and gives the best possibility that they aim for a STEM job. Archer Ker et al. (2013) mentions that students who come from families with low science capital are unlikely to develop STEM job aspirations by 14-years-old if they are not already interested by the age of 10. Most students enjoy science lessons thus indicating that many students do already have an interest in the subject.

These results are illustrated in fig. 5.8.

5.2.6 Favourite Science Topic

What part of science lessons do you like the most?
(*Pa rhan o wyddoniaeth wyt ti'n hoffi'r mwyaf?*)

Identifying which science topics students find most engaging is essential for evaluating whether space-related workshops are valuable and broadly appealing to students. This insight helps determine whether the Comet Chasers concept is likely to capture students' interest, particularly if space is already a topic they find exciting and willing to learn more about. This question was multiple choice with an option to input their own topic if they so wish.

TABLE 5.10: Summary of students' favourite topics in science lessons. Those who opted not to answer were not counted.

Ranking	n	(%)
Space	69	(39.4%)
Experiments	38	(21.7%)
Animals and Plants	34	(19.4%)
Human Body	15	(8.6%)
Computers	14	(8.0%)
Other	5	(2.9%)
Total	175	(100%)

What part of science lessons do you like the most?

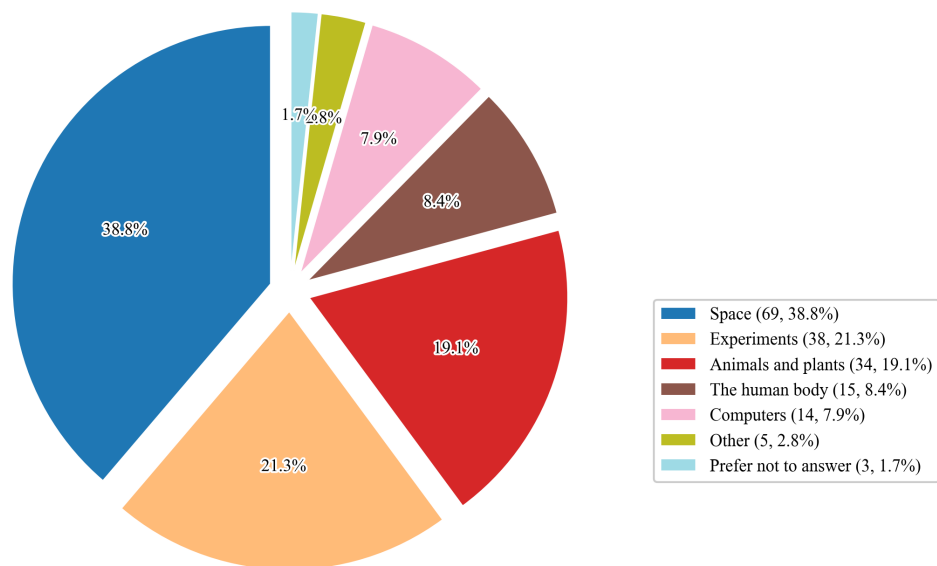


FIGURE 5.9: Pie chart displaying students' responses when asked for their favourite topic within science (N=175). Multiple options were supplied with the option to input their own if they wish. Space dominates as the favourite topic consisting of 39.4% of all responses.

Space was the most frequently selected as a favourite topic among all students surveyed, 69 responses selected space (39%). Although the data clearly show a preference for space, it is important to acknowledge again that this may not be representative of all students in this age group. Students may have been aware

that they were participating in a space-themed workshop and could have perceived “space” as the expected or “correct” answer. As mentioned, it is also possible that teachers selected students for the workshop based on their known interest in space. Furthermore, some schools may have chosen to participate in the workshops because of recent or ongoing lessons focused on space. Several teachers mentioned that their classes had recently spent a semester studying space, which contributed to the students’ knowledge and enthusiasm for the workshop. Data depicted in fig. 5.9.

These three factors may have influenced the responses collected in this question. This context becomes especially important when comparing the popularity of space with other science topics. Topics such as animals and plants, experiments, the human body, and computers received relatively similar levels of interest, suggesting a more evenly distributed preference across these areas.

‘Experiments’ was also a popular choice of topic within science, with 38 responses selecting it (22%). Conducting experiments are the most dynamic and involved parts of science lessons in school. Murphy and Beggs (2003) and Blankenburg et al. (2016) suggest that experiments help students remember concepts better than conventional lessons, and has been viewed as a positive way to engage students with science (Susiloningsih et al. 2025).

Assuming that these results are representative and unbiased, space would be a great vehicle for teachers to introduce new scientific (and potentially non-scientific) concepts - it is exciting and novel for the students, meaning that they are more willing to listen and learn about the work. A gateway for further learning is always valuable and could lead the students to researching topics themselves.

By comparing students’ enjoyment of science lessons with their favourite science topics, we can better understand what appeals to both students who enjoy science lessons and those who do not.

TABLE 5.11: Favourite science topics by students' enjoyment level of science lessons (dislike, neutral, like). Percentages reflect the share of students within each enjoyment group.

Favourite Topic	Science Ranking			Total
	Dislike (1-2)	Neutral (3)	Like (4-5)	
Space	6 (38%)	16 (36%)	45 (41%)	67 (39%)
Experiments	2 (13%)	9 (20%)	27 (25%)	38 (22%)
Animals/Plants	2 (13%)	8 (18%)	24 (22%)	34 (20%)
Human Body	3 (19%)	7 (16%)	5 (5%)	15 (9%)
Computers	3 (19%)	4 (9%)	7 (6%)	14 (8%)
Other	0 (0%)	1 (2%)	2 (2%)	3 (2%)
Total	16 (9%)	44 (26%)	110 (64%)	171 (100%)

Space was the most popular topic for all students, regardless of their enjoyment score of science lessons. It is twice as popular as any other topics for those who ranked science lessons a 1 or 2, suggesting that it is a good vehicle to engage students who are not interested or dislike science lessons. It is also popular amongst those who ranked science lessons 3+.

5.2.7 Space Enjoyment

Do you enjoy learning about space?

(Wyt ti'n mwynhau dysgu am y gofod?)

Pairing this question with the following one (Section 5.2.8) provides insight into how much students enjoy learning about space and how motivated they are to explore the topic further. This comparison helps determine whether astronomy has broad appeal or resonates strongest with a specific subset of students.

A total of 65.4% of students rated their enjoyment of learning about space as 4 or 5, compared to 57.9% for science lessons overall. This difference is even more pronounced when looking specifically at the highest rating: 44.7% of students gave space a 5, compared to 30.9% for science lessons. While these results are promising, they may not definitively indicate the success of space as a universally engaging topic. There is also a slight increase in students who reported

TABLE 5.12: Summary of the ranking of how students enjoy learning about space in science lessons. 1 means that students ‘do not like science at all’, and 5 means that ‘they love them’.

Ranking	n	(%)
1	12	(8.0%)
2	14	(9.3%)
3	26	(17.3%)
4	31	(20.7%)
5	67	(44.7%)
Total	150	(100%)
Weighted average	3.85	
Median	4	
Mode	5	
NPS	48.0%	

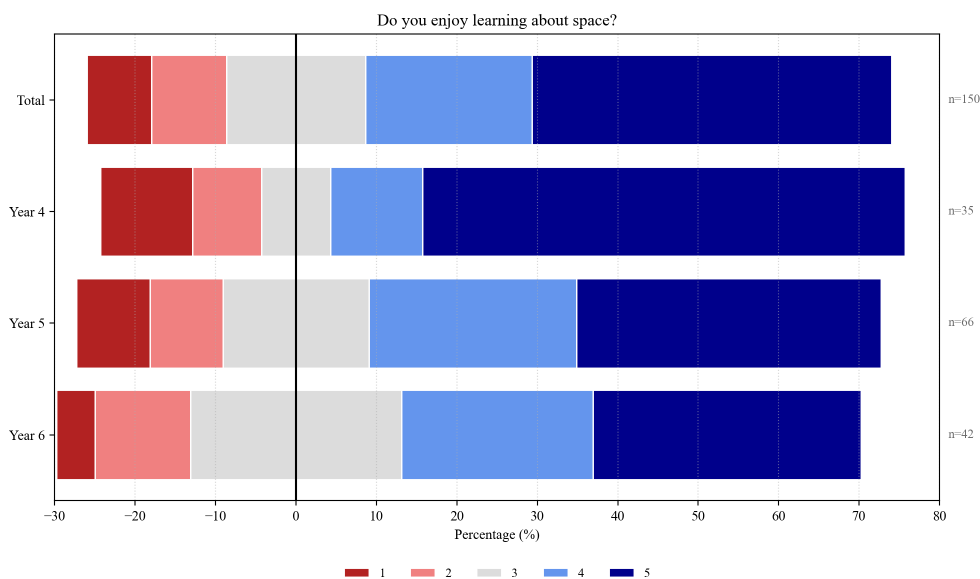


FIGURE 5.10: Students' opinions on their enjoyment of learning about space in science lessons (N=150). 1 represents hating the topic, and 5 represents loving the topic. Breakdown of year group's opinions are displayed.

TABLE 5.13: Distribution of students' enjoyment of learning about space, grouped by their enjoyment of science lessons. Columns represent science enjoyment levels; rows show how students in each group rated their enjoyment of space (1 = dislike, 5 = love).

Space Ranking	Science Ranking			Total
	Dislike (1-2)	Neutral (3)	Like (4-5)	
1	8 (42%)	2 (5%)	2 (2%)	12 (8%)
2	3 (16%)	9 (20%)	2 (2%)	14 (9%)
3	4 (21%)	10 (23%)	12 (14%)	26 (17%)
4	3 (16%)	12 (27%)	15 (17%)	30 (20%)
5	1 (5%)	11 (25%)	55 (64%)	67 (45%)
Total	19 (13%)	44 (30%)	86 (58%)	149 (100%)

disliking space (17.3% rated it 1 or 2), compared to those who disliked science lessons overall (12.5%). It is reasonable to assume that students who do not enjoy science are unlikely to enjoy learning about space. However, the reverse is not necessarily true — students who enjoy science may not automatically find space engaging. This is understandable, as science encompasses a wide range of topics, and enjoyment of one area does not guarantee interest in another.

Again, we see a decrease in enjoyment as students age, following findings by Murphy and Beggs (2003). The proportion of student who ranked their enjoyment of learning about space either a 1 or 5 decreases, with older students having higher proportions of neutrality towards the topic (ranked 3).

Despite being one of the most popular favourite science topics, space appears to be more polarising than students' overall opinions of science lessons. Both extreme rankings (1 and 5) show an increased proportion of students' enjoyment of learning about space compared with their rankings for their enjoyment of science lessons.

Tab. 5.13 shows how students responded to the question about learning about space with respect to their rating of enjoying science lessons. For those who like science lessons, students are very likely to also enjoy learning about space (65% of students who enjoy science lessons enjoy learning about space). This is promising, suggesting that students who like science will likely enjoy learning

about space. Interestingly, one student who rated their enjoyment of learning about space as 1 also listed space as their favourite science topic — highlighting either the complexity of individual preferences, a lack of clarity in the questionnaire, or lack of understanding on the respondent's part.

Of those who specified that they did not enjoy science lessons (ranked 1 or 2), their enjoyment of learning about space can be seen in tab. 5.13. As this group is smaller than those who enjoy science, any conclusions drawn should be interpreted with caution. Among students who reported disliking science lessons, the most common response was a strong dislike for learning about space — an expected outcome. However, a few students in this group expressed neutral or even positive attitudes toward space, suggesting that the topic may still hold appeal for some.

For those students who are neutral about enjoying their science lessons (ranking 3), their enjoyment of learning about space can be seen in tab. 5.13. This group leans toward enjoying space, with 46% rating it positively and 15% negatively.

5.2.8 More Space?

Do you want to learn more about space in school? (Wyt ti eisiau dysgu mwy am y gofod yn ysgol?)

Students' desire to learn more about space received slightly fewer positive responses compared to the previous question, though the difference was marginal. The weighted average was 3.73, just 0.12 lower than the 3.85 recorded for Question 9. This negligible difference may be attributed to the limited sample size.

Overall, the responses to this question reinforce the findings from the previous question: students have a strong interest in space, with almost half (45.1%) opting for the highest rating. This is higher than the previous question, further adding to the appeal of learning about space. The similarity in responses suggest that students both enjoy learning about space and are motivated to explore it further in lessons.

TABLE 5.14: Student responses to the question: “Do you want to learn more about space in school?” Responses are ranked from 1 (not at all) to 5 (really want to learn more). This question aimed to assess students’ motivation to further explore astronomy topics in the classroom.

Ranking	n	(%)
1	14	(9.2%)
2	19	(12.4%)
3	30	(19.6%)
4	21	(13.7%)
5	69	(45.1%)
Total	153	(100%)
Weighted average	3.73	
Median	4	
Mode	5	
NPS	37.3%	

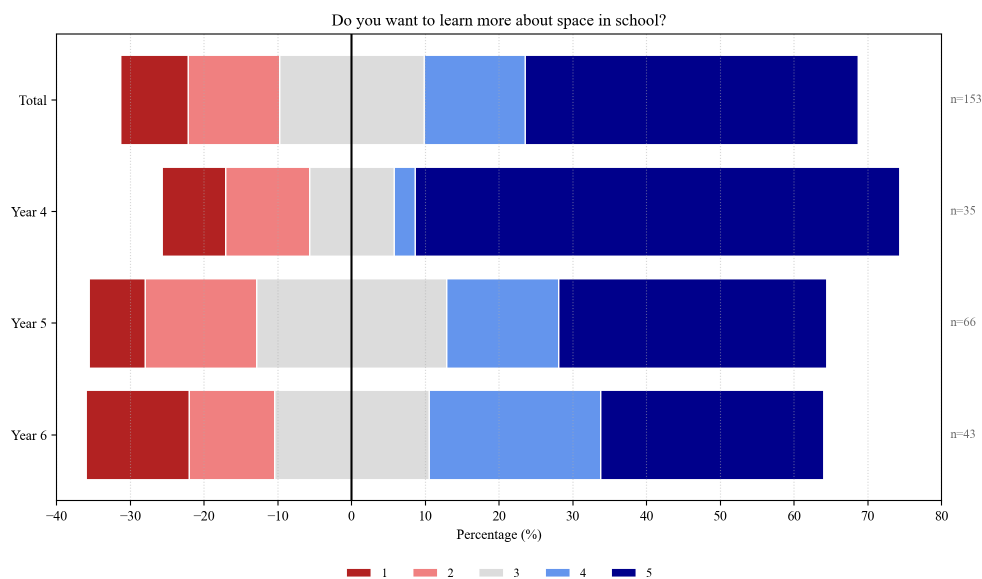


FIGURE 5.11: Distribution of students’ responses to the question: “Do you want to learn more about space in school?” A rating of 1 indicates no interest, while 5 indicates a strong desire to learn more. This figure visualises the overall enthusiasm for further space-related learning. Breakdown of year group’s opinions are displayed (N=153).



FIGURE 5.12: Images that students were required to identify. Multiple choice options were given, which students had to match with the image.

5.2.9 Knowledge Test

This question aimed to assess students' baseline knowledge of common astronomical objects. Students were shown images of five different celestial objects — meteor, comet, star, galaxy, and planet — and asked to match each image with its correct label. No correct/incorrect indicators were given to the students as this may interfere with results from other students. This approach also helped avoid discouraging lower-ability students or encouraging comparison of scores among peers.

A total of 59 students (39%) correctly identified all five celestial objects. Given students completed this questionnaire before the workshop, some teachers may have helped the students identify the objects, causing an unrepresentative result - this must be accounted for when assessing these results.

As shown in fig. 5.13, students most accurately identified stars, planets, and galaxies, with a high proportion selecting the correct answers for these objects.

Stars are likely easier to identify due to their visibility in the night sky and familiarity from everyday experience. Planets and galaxies are also visually distinctive and frequently featured in media and educational content, which may aid recognition. In contrast, meteors and comets were more difficult to identify, with correct responses around 50%. This confusion is understandable, as (still images of) meteors and comets can appear visually similar and are less frequently discussed in mainstream media. This is supported by the fact that the second most common response for each was either ‘meteor’ or ‘comet’. Additionally, comets and meteors are not objects seen in the sky every night, they are rare events passing by/into the Earth occasionally. While meteorites are common, they can be easily missed.

This highlights that students are not as aware of comets as they are of galaxies or planets. This is both a positive and a negative for the programme, and introduces additional complications. As students are less aware of comets, they might not be as excited for a project based around comets. This attitude could transfer into the lesson with students not wanting to be as engaged as they could be. A positive is that there is scope for students to learn more about these objects given that they are neglected in the regular curriculum and/or in the media.

TABLE 5.15: Cross-tabulation of students’ quiz scores (0–5) and their enjoyment of science lessons (dislike (score 1-2), neutral (score 3), and like (score 4-5), showing counts and percentages (N = 152). Summary statistics (weighted average, mode, median, and Net Promoter Score) appear below, reflecting central tendencies and enthusiasm levels.

Science Ranking	Quiz Score						Total
	0	1	2	3	4	5	
Dislike (1-2)	4 (27%)	5 (26%)	1 (10%)	7 (17%)	0 (0%)	2 (3%)	19 (13%)
Neutral (3)	4 (27%)	6 (32%)	2 (20%)	13 (31%)	2 (29%)	18 (31%)	45 (30%)
Like (4-5)	7 (47%)	8 (42%)	7 (70%)	22 (52%)	5 (71%)	39 (66%)	88 (58%)
Total	15 (10%)	19 (13%)	10 (7%)	42 (28%)	7 (5%)	59 (39%)	152 (100%)
Weighted Average	3.47	3.42	4.00	3.48	4.14	3.98	3.73
Median	2	3	4	4	4	4	4
Mode	3	5	5	4	5	5	5
NPS	20.0%	15.8%	60.0%	35.71%	71.4%	62.7%	45.4%

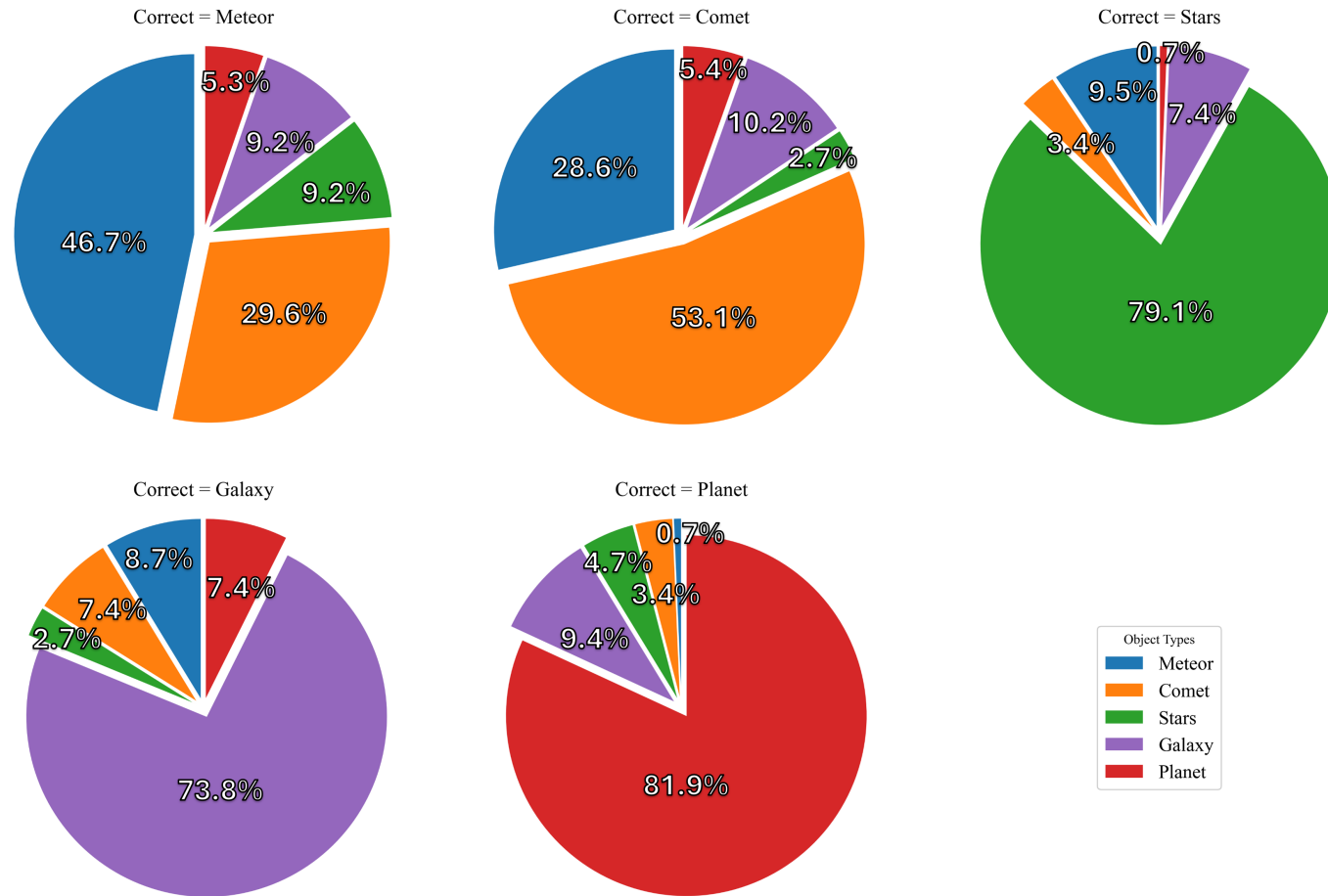


FIGURE 5.13: Results from the astronomy image-matching quiz. Students were asked to identify five celestial objects: a meteor, comet, star, galaxy, and planet. The figure shows the distribution of correct and incorrect responses for each object.

TABLE 5.16: Cross-tabulation of students’ quiz scores (0–5) and their enjoyment of learning about space (dislike (score 1-2), neutral (score 3), and like (score 4-5), showing counts and percentages (N = 150). Summary statistics (weighted average, mode, median, and Net Promoter Score) appear below, reflecting central tendencies and enthusiasm levels.

Space Ranking	Quiz Score						Total
	0	1	2	3	4	5	
Dislike (1–2)	5 (33%)	4 (21%)	1 (10%)	8 (20%)	1 (14%)	7 (12%)	26 (17%)
Neutral (3)	3 (20%)	4 (21%)	0 (0%)	8 (20%)	1 (14%)	10 (17%)	26 (17%)
Like (4–5)	7 (47%)	11 (58%)	9 (90%)	25 (61%)	5 (71%)	41 (71%)	98 (65%)
Total	15 (10%)	19 (130%)	10 (7%)	41 (27%)	7 (5%)	58 (39%)	150 (100%)
Weighted Average	3.27	3.58	4.60	3.66	4.14	4.05	3.85
Median	3	4	5	4	5	5	4
Mode	5	5	5	5	5	5	5
NPS	13.3%	36.8%	80.0%	41.5%	57.1%	58.6%	48.0%

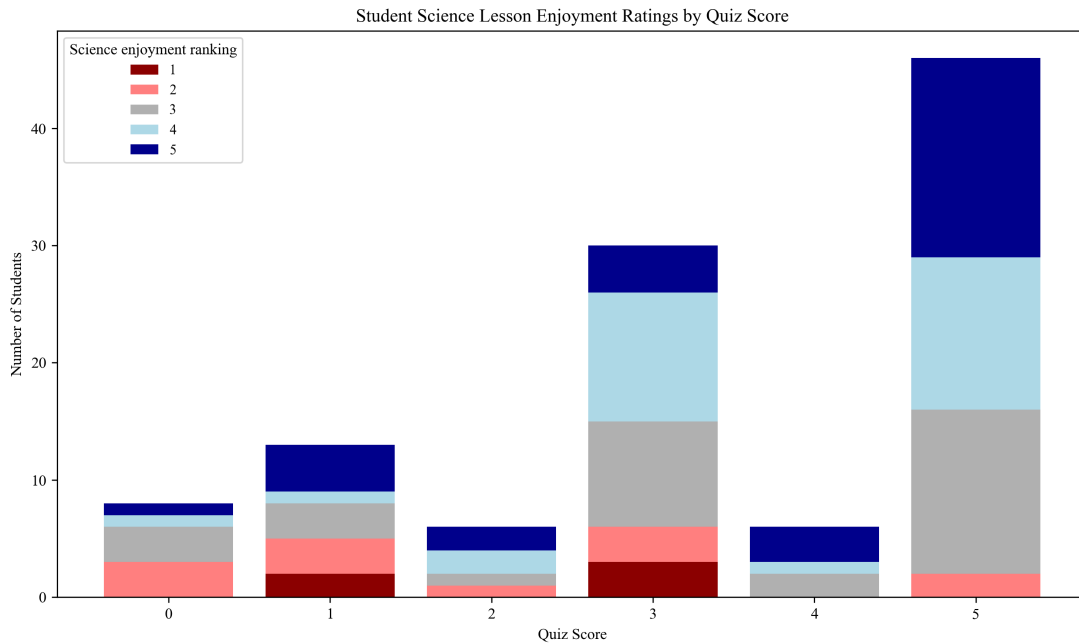


FIGURE 5.14: Distribution of students' quiz scores (0-5) with respect to their enjoyment of science lessons (1 = Dislike, 4= Love) in the form of a stacked bar chart (N=150).

All score groups had a weighted average greater than 3, the neutral value, implying that the students do not view science lessons negatively as a whole, regardless of their quiz score. This value broadly trends positively as the score increases, and scores 2 and 4 are outliers to this trend - most likely due to their smaller sample size. The mode for each score group is positive (4 or 5) other than for those who scored 0.

This dataset implies that students who score lowest (scores of 0 or 1) would view science lessons slightly more positively. Students who perform poorly at tests or who are limited in their knowledge of science are not necessarily going to strongly dislike science lessons. It is important to ensure that students at lower scientific abilities are able to engage and interact with the material as they would have the most to gain by increasing their interest in the subject.

As expected, students who performed well on the quiz are more likely to enjoy science lessons in all analytical methods calculated. This is not surprising, as these students would be most likely to retain information learned both in science lessons and via extracurricular sources.

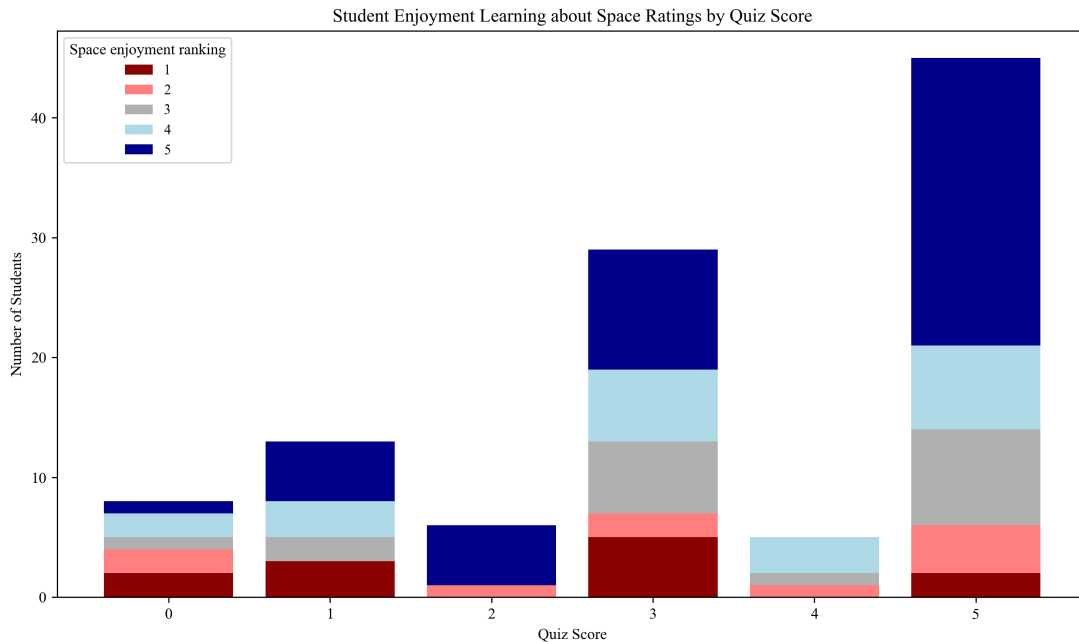


FIGURE 5.15: Distribution of students' quiz scores (0-5) with respect to their enjoyment of learning about space (1 = Dislike, 5= Love) in the form of a stacked bar chart.

Students' opinions of learning about space may be more representative of their interest in the topic compared with their opinion of science lessons, as they may not enjoy science lessons in school due to a myriad of factors external to the students' interest levels. This certainly appears to be the case when comparing responses to questions in sections 4.1.7 and 4.1.8. We see in fig. 5.15 the proportion of those who ranked their enjoyment of learning about space as a 4 or 5 is higher than that for fig. 5.14 for most score groups. It is imperative to ensure that those who do not view space positively are not alienated from the activities available in the Comet Chasers' workshops.

5.2.10 Summary

Questionnaires were distributed to classes prior to their participation in a Comet Chasers' workshop to assess students' interest in science and astronomy, as well as their broader science capital. Of the 12 schools invited to complete the survey, 7 participated, yielding 154 responses.

Almost half of the respondents were in Year 5, with around a quarter in Year 4 and Year 6. Four of the participating classes were mixed-year groups (Years 4 and 5 or Years 5 and 6), while the remaining three were single-year classes. The number of responses per school ranged between 5% to 29% of the total sample.

The most frequently desired career fields were [STEM](#) (22%), Sport (19%), and Art (18%). Interestingly, among those who aspired to a [STEM](#) career, the most frequently selected favourite subjects were Art and PE. This suggests that students may not fully understand the academic pathways required for [STEM](#) careers, or may not associate their desired jobs with [STEM](#) subjects.

When asked about their favourite subject overall, students most frequently selected Art (27%), followed by Maths (23%), and PE (19%). Science was only chosen by 7% of respondents.

Regarding [STEM](#) role models, 16% of students reported knowing someone who works in a [STEM](#) field, while 40% did not, and the remainder were unsure. Those who did know someone in [STEM](#) were more likely to cite family friends or extended family. There was no increase in interest in a [STEM](#) career among these students.

Students were asked to rate their enjoyment of science lessons on a scale from 1 (dislike) to 5 (love). The responses were generally positive, with a weighted average of 3.73 and a [Net Promoter Score \(NPS\)](#) of 45.4%. Students seem to enjoy learning about space more than compared with their enjoyment of science lessons. The weighted average score and [NPS](#) were slightly higher (3.85 and 48.0%, respectively), suggesting more positive opinions towards the topic.

Interest in learning more about space was lower, with a weighted average of 3.73 and an [NPS](#) of 37.3%. Despite this, when asked to select their favourite scientific topic, 39.4% selected 'Space', supporting Comet Chasers' hypothesis that astronomy is a highly engaging subject for young learners.

Finally, students completed a short quiz to match astronomical objects with their name. Most students correctly identified planets, stars, and galaxies, while

comets and meteors were more frequently confused. This highlights a gap in the students' exposure to less commonly discussed astronomical phenomena. Notably, those who performed well on the quiz were more likely to report enjoying science lessons and space, although lower quiz scores did not necessarily correlate with disinterest.

Key findings:

- [STEM](#) jobs were the most popular choice for students, followed by a career in sport, then art.
- Art and Maths were the two most popular school subjects, followed by PE.
- Under 20% of students knew someone who worked in a [STEM](#) field, with that relative being extended family or family friend.
- Students generally had positive opinions on Science lessons.
- Interest in learning about space is higher than for science lessons and was selected as the most popular topic within science.
- Respondents could identify planets, stars, and galaxies, while struggling to identify comets and meteors.

5.3 Post-Engagement Evaluation

This questionnaire aimed to assess the students' opinions following their engagement with the Comet Chasers workshops. Most questions asked students to either rank activities on a 1-5 scale or respond to open-ended prompts about their likes, dislikes, and suggestions for improvement. Questions are specific to the different activities, including a section for the workshop as a whole.

5.3.1 Respondent Demographics

What school year are you?
(Pa flwyddyn ysgol wyt ti?)

To understand the age distribution of participants in the post-engagement survey, students were asked to indicate their current school year. The responses are summarised in Table 5.17 and visualised in fig. 5.16.

TABLE 5.17: Distribution of student respondents by school year in the post-engagement questionnaire. The majority of responses came from Year 6 students, with smaller proportions from Years 4 and 5. A small number of students chose not to disclose their year group.

School Year	Number of students	%
Year 4	18	24.0%
Year 5	18	24.0%
Year 6	33	44.0%
PNTA	6	8.0%
Total	75	100%

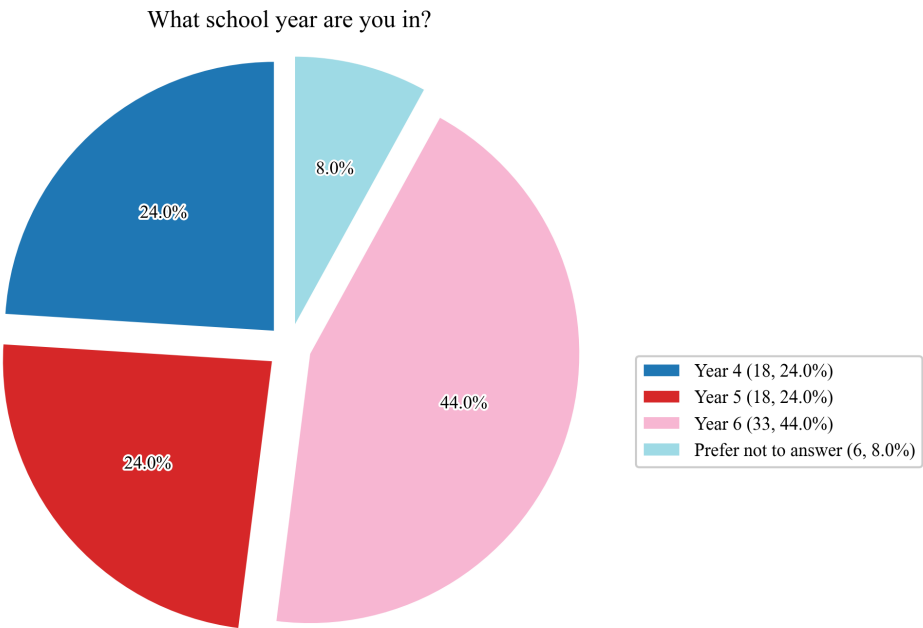


FIGURE 5.16: Pie chart showing the distribution of school years among students who participated in the post-engagement survey (N=75). Year 6 students represented the largest group of respondents.

Year 6 students comprised the largest group, accounting for 44% of respondents. Year 4 and 5 students were equally represented, at 24% of the sample. A small proportion of students (8%) chose not to disclose their year group.

This distribution differs from the pre-engagement survey, which had a higher proportion of Year 5 students. The shift in year group representation may influence the comparability of responses between the two surveys, particularly if age-related factors affect engagement or recall. The smaller sample size (N=75) also limits direct comparisons between the two datasets.

What is the name of your school?

(Beth ydi enw dy ysgol?)

This question was slightly rephrased after assessing responses from the pre-engagement questionnaire to reduce confusion. In the pre-engagement survey, a student responded to the question ‘What school do you go to?’ with the secondary school they would be attending in the next academic year - the phrasing in Welsh (‘Pa ysgol wyt ti’n mynd i?’) caused the ambiguity as it could mean ‘Which school are you going to?’. This is an issue that arose due to the intentionally informal language used in the questionnaire. Thankfully, it was simple to identify the school of that particular student due to local knowledge of the area and timings when they completed the questionnaire. Rephrasing to ask what their school is called is a far clearer way to phrase the question, for both languages.

Five of the twelve schools invited to complete the post-engagement questionnaire provided responses. Tab. 5.18 presents a cross-tabulation of the distribution of student year groups for each school that responded to the post-engagement questionnaire. Each row represents one school, while each column represents the year group. Percentages in the year columns indicate the proportion of students from each year within that school, while the percentages in the ‘Total’ column reflect each school’s contribution to the overall sample. Note: the school labels (e.g., School C, D, etc.) are consistent with those used in the pre-engagement survey to allow for cross-referencing.

TABLE 5.18: Distribution of student year groups by school for the pre-engagement questionnaire. Percentages in brackets indicate the proportion of each year group within that school. The ‘Total’ column shows each school’s contribution to the overall sample.

School	Year 4	Year 5	Year 6	PNTA	Total
C	0 (0%)	4 (24%)	12 (71%)	1 (6%)	17 (23%)
D	0 (0%)	12 (57%)	9 (43%)	0 (0%)	21 (28%)
E	8 (67%)	1 (8%)	3 (25%)	0 (0%)	12 (16%)
G	0 (0%)	1 (10%)	9 (90%)	0 (0%)	10 (13%)
H	10 (67%)	0 (0%)	0 (0%)	5 (33%)	15 (20%)
Total	18 (24%)	18 (24%)	33 (44%)	6 (8%)	75 (100%)

School D submitted the highest number of responses, followed by C, then H.

Most schools that responded were mixed-year groups, with school H likely to be a single-year group (cannot be certain due to the ‘PNTA’ responses).

5.3.2 Rotato Evaluation

Summary of Rotato activity can be read in sect. [2.4.1.3](#).

5.3.2.1 Did you enjoy the Rotato?

Did you enjoy doing the Rotato experiment?

(Wnes ti mwynhau gwneud yr arbrawf Rotato?)

It is important to assess the students’ overall opinions on each activity. A 1-5 rating scale was used to assess how engaging and enjoyable the students found the activity.

Note: this activity was not conducted with school F, therefore their responses have been omitted. Additionally, students who did not supply their school year have been omitted - this only affected one student and they did not supply a ranking for this question.

TABLE 5.19: Student responses to the question: “Did you enjoy doing the Rotato experiment?” Responses are ranked from 1 (dislike) to 5 (love). This question aimed to assess students’ overall feelings about the Rotato experiment.

Ranking	Year 4	Year 5	Year 6	Total
1	0 (0%)	2 (11%)	2 (6%)	4 (7%)
2	1 (13%)	3 (17%)	1 (3%)	5 (9%)
3	2 (25%)	4 (22%)	8 (24%)	14 (24%)
4	2 (25%)	6 (33%)	13 (39%)	21 (36%)
5	3 (38%)	3 (17%)	9 (27%)	15 (25%)
Total	8 (14%)	18 (31%)	33 (56%)	59 (100%)
Weighted average	3.88	3.50	3.79	3.73
Median	4	3.5	4	4
Mode	5	4	4	4
NPS	50.0%	22.2%	57.3%	45.7%

The weighted average of 3.73 and **NPS** of 45.7% suggest a generally positive reception, though with room for improvement. Splitting these results by year group, Year 5 students enjoyed the activity the least, with a weighted average of 3.50 and **NPS** of 22.2% - despite a lower ranking, Year 5 students still viewed the activity positively. Students in Year 6 enjoyed the activity the most, with a weighted average of 3.79 and **NPS** of 57.3%. Given the small sample size for Year 4 respondents, these results must be taken more critically. It is possible that the ‘more able’ Year 4 students were chosen to take part in the workshops by their teachers as the introductory email specified that the workshop was most appropriate for Years 5 and 6. If this is the case, this sample of Year 4 students is not representative of the general Year 4 population.

Regardless, the data suggests that Year 6 students enjoyed the activity more than Year 5 students, with lower proportions of students ranking the activity negatively (1 or 2), suggesting that this activity is better suited for older students. This makes sense given that this is the least hands-on activity, and requires patience and thought to deduce the conclusions of the activity. Younger students may not be as willing to take their time needed to produce and analyse the plots, and resort to e.g. piling soft toys onto the turntable. It would be

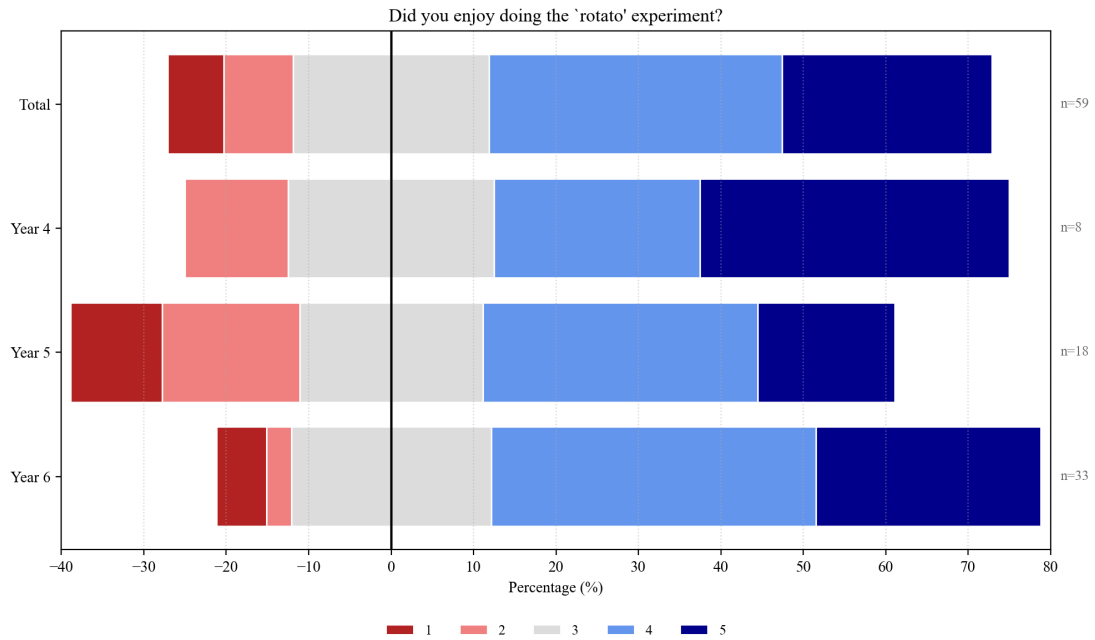


FIGURE 5.17: Diverging stacked bar chart showing the total proportions of responses to the survey question: “Did you enjoy doing the Rotato experiment?”, as well as the distribution broken down by year group. Bars are centred on a neutral midpoint to highlight positive and negative response patterns.

useful to adapt the activity to be more fast-paced, with more directions given to younger students with the aim of further engaging them in the activity. While differing enjoyment ranking between school years, a Kruskal–Wallis test found no statistically significant differences between year groups ($H(2) = 2.30$, $p = 0.317$).

5.3.2.2 Learning Points

What did you learn by using the Rotato?

(Be wnes ti dysgu wrth ddefnyddio'r Rotato?)

This question aimed to discover what aspects, from conducting the experiment, were most memorable for the students. Ideally, all students would respond with explaining how lightcurves are produced for real objects in space, although this is unlikely. Open responses should provide an insight into what stood out the

most for students, and help identify the parts they found most interesting - giving more freedom to express their feelings, although it does make analysis more complex. The methods used to analyse these responses are explained in section 2.5.2.

Note: As mentioned in section 5.3.2.1, students from school F were excluded for questions related to the Rotato experiment as they did not take part in the activity. PNTA responses were excluded.

TABLE 5.20: Summary of the thematic categories used to analyse the responses for the question ‘What did you learn by using the Rotato?’. The number of responses which fall into each category are listed along with its percentage. PNTA responses were excluded.

Thematic Category	n	(%)
Light and Reflection	15	(28%)
Graphs and Measurements	9	(17%)
Don’t Remember/Don’t Know	7	(13%)
Learning and Understanding	4	(8%)
Objects and Space	3	(6%)
Rotation and Movement	3	(6%)
Other/Unclear	6	(11%)
Unrelated	5	(9%)
Total	53	(100%)

Students were most likely to mention that they learned something about ‘Light and Reflection’, with 15 respondents (28%) discussing that they had learnt how light behaves and reflects off objects. Responses within this category include: how black absorbs light and white reflects it; how shining light increases the detected brightness of an object, and how light can ‘bounce’ off objects.

These students understood the content in different ways, with some stating how light is absorbed/reflected fairly clearly, e.g. “*Mae du yn amsugno golau ac mae gwyn yn bownsio golau i fwrdd.*”

Translation: “Black absorbs light and white bounces light away.” (Year 6, School C)

Some students explained the concept in terms more familiar to them, e.g. *“pam mae y galau fynd ar y darnau gwyn o'r penguin nes o'r reflecutior golau [sic]”*²

Translation: “When the light goes on the white parts of the penguin it reflects the light” (Year 6, School D)

A large plush penguin was used as the demo to explain how the Rotato experiment works - this is a perfect demo to explain that white reflects the light and black absorbs it, as seen in fig. 2.11a.

These two responses highlight differences in how students are able to understand abstract concepts. Some may be able to verbalise knowledge learned in general terms, while some require something more tangible to express their knowledge. It is important that workshops in schools are able to cater to both types of students, and all those in between.

‘Graphs and Measurements’ was another popular theme, with 9 (17%) responses falling into these categories. Five of these responses were also identified to be in the ‘Light and Reflection’ category. This is understandable as variations in light caused changes in the graph, showing that these students understand this innate connection.

Most of these students correctly identified that the greater the intensity of incident light on an object, the higher the line on the lightcurve is.

“bod golau yn gwneud y graff fynd yn uwch”

Translation: “That light makes the graph go up” (Year 6, School G)

“Pryd oedd ti rhoi gola ar y pethau oedd o mynd yn llachar [sic]”

Translation: “When you put light on the things it became bright [sic]” (Year 4, School E)

While a fairly basic concept regarding the activity, it is good that students are able to identify this aspect of the software output. This is one of the core concept for photometric measurements - the more incident light, the higher the

²I believe this is meant to read *“pan mae y golau yn mynd ar y darnau gwyn o'r penguin nath o'r reflectio'r golau [sic]”*

measured brightness. It is therefore good to confirm that students are aware of this fact following the activity, as introducing a deeper investigation into photometry would make more sense to them than to students who had not first completed the activity. Responses did not touch on other important aspects of photometry, such as albedo or size of object, suggesting that this did not remain in the students' mind following the activity.

A non-trivial number of student responses consisted of the fact they could not remember what they had learned from the Rotato activity. 7 students (13%) mentioned they did not remember or did not know what they had learnt.

“dwi wedi anghofio”

Translation: “I’ve forgotten”

(Year 5, School C)

“dwi ddim yn cofio.”

Translation: “I don’t remember”

(Year 6, School D)

It is important to note that these students did not complete the questionnaire immediately after the session, instead completing them roughly a month after the intervention. For a student at this age, this is a long time to remember a one-hour workshop. That being said, these responses were some of the first to be returned following the workshop. This does highlight that post-engagement evaluation needs to be completed as closely to the workshop as possible, ideally immediately afterward.

5 students (9%) responded to this question with what they learned from the other activities. While it is pleasing to see that students learned about comets from the initial presentation, it does not help the specific analysis of the Rotato experiment. Adaptations must be made to the questionnaire to ensure that it is made clear to students that the question relates specifically to the Rotato experiment. Using images of the activities at the beginning of each section could help clarify any ambiguity.

Respondents cited learning mostly about ‘Light and Reflection’ and ‘Graphs and Measurements’, touching on aspects of how different colours affect reflected

light, how light behaves, and how lightcurves display the brightness of an object over time. These are insightful learning points which make up the core concepts of how and why photometry is such an effective tool for astronomers. While students would likely learn other learning points from this activity, leaving the workshop with this knowledge alone gives them a good basis to begin diving further into photometry and how astronomers can investigate the Universe. The activity sets up the students' potential involvement with the Comet Chasers' programme positively, to help engage them in the real science and to understand these processes.

5.3.2.3 Favourite Aspect

What was the best part of the Rotato?

(Be oedd y rhan orau o'r Rotato?)

TABLE 5.21: Summary of the thematic categories used to analyse the responses for the question 'What was the best part of the Rotato?'. The number of responses which fall into each category are listed along with its percentage. [PNTA](#) responses were excluded.

Thematic Category	n	(%)
Exploration and Interaction	9	(16%)
Graphs and Measurement	7	(12%)
Rotation and Movement	7	(12%)
Objects and Materials	6	(10%)
Don't Remember/Don't Know	5	(9%)
Light and Reflection	4	(7%)
General Enjoyment	3	(5%)
Other/Unclear	7	(12%)
Unrelated	10	(17%)
Total	58	(100%)

This question resulted in a fairly even spread of the different categories that students found most enjoyable following this activity - implying a broad range of what students found the 'best' about the Rotato.

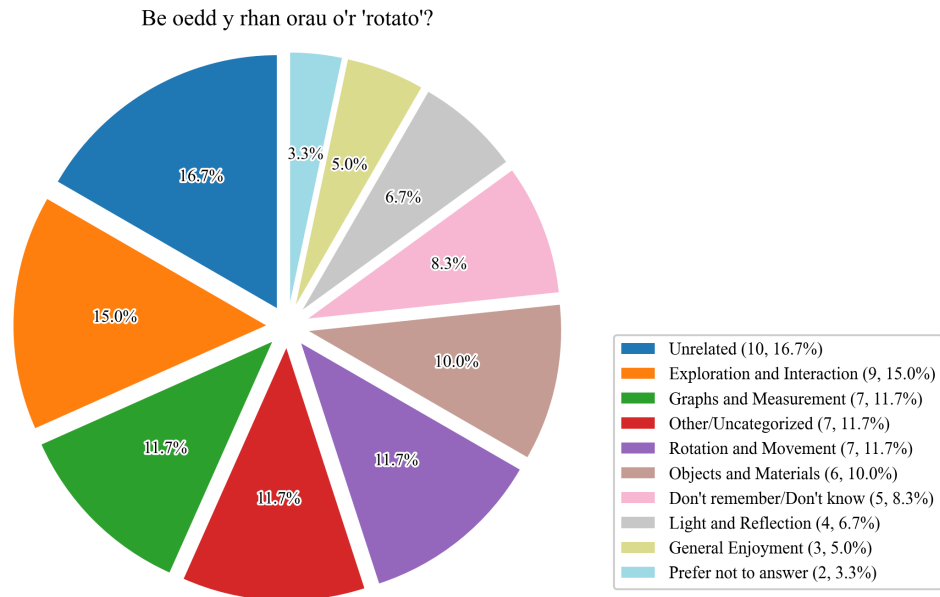


FIGURE 5.18: Responses for “What was the best part of the Rotato?”

The largest category was ‘Exploration and Interaction’ with 9 responses (16%). Responses mainly touched on using different items to test on the turntable to change the lightcurve reading, while some mentioned more broadly that they liked observing what occurred, e.g.

“Cael defnyddio pethau gwahannol i fynd ar y pethau sydd yn rotato”

Translation: “Using different items to go on the Rotato” (Year 6, School E)

“trio pethau whanol ac gweld y tonau yn mynd i fyny”

Translation: “Trying different items and seeing the waves go up” (Year 4, School E)

The students liked the interactiveness of the activity, with the ability to test different objects to measure their lightcurves. All students who had responses within this category ranked the activity as a 3 or 4 out of 5.

Both the ‘Graphs and Measurements’ and ‘Rotation and Movement’ categories had 7 responses (12%) each.

Responses in the ‘Graphs and Measurements’ category cited that they liked the graph creating the lightcurve, e.g.

*“pam oedd ti rhoidy golau fynd off a on wedyn oedd y chartfynd rely uchel wedyn
‘rely isel [sic]”*

*Translation: “When you put the light off and on then the chart went really high
then really low”* (Year 6, School D)

“Y Graff”

Translation: “The Graph” (Year 6, School G)

Perhaps as expected, all respondents within this category were predominantly in Year 6, with one respondent in Year 5. The older students would have more exposure to using graphs from their (more advanced) maths and/or science lessons at school. These responses suggest that the Rotato is better suited for older students, to ensure that students gain the most value from the activity.

For the category ‘Rotation and Movement’, respondents noted that they enjoyed seeing objects rotate, particularly the plush toys, e.g.

“gweld yr anifeiliaid yn troi,a troi,a troi”

Translation: “Seeing the animals turn, and turn, and turn” (Year 5, School D)

“yr bethau yn symud”

Translation: “The things moving” (Year 4, School E)

“Gweld yr ddraig yn troi.”

Translation: “Seeing the dragon turn” (Year 6, School D)

3 of the 7 responses in this category were from students in Year 4, suggesting this may be more appealing to younger students. The use of objects like plush toys is a good way to ensure that younger students are involved in the activity, and that they are able to enjoy it.

Respondents had a broad variety of aspects that they liked the most about the Rotato activity. The most popular categories of the responses consisted of ‘Exploration and Interaction’, ‘Graphs and Measurements’, ‘Rotation and Movement’, and ‘Objects and Materials’. Students enjoyed the interactiveness and

experimental nature of the activity, with some enjoying using the graphs, and some enjoying watching the objects rotate on the turntable.

5.3.2.4 Dislikes

What didn't you like about the Rotato?

(Be wnes ti ddim hoffi am y rotato?)

This question aimed to assess what aspects the students find least enjoyable with the Rotato experiment. This gives us a better indication which aspects of the activity requires work to ensure that students are able to enjoy it as much as possible.

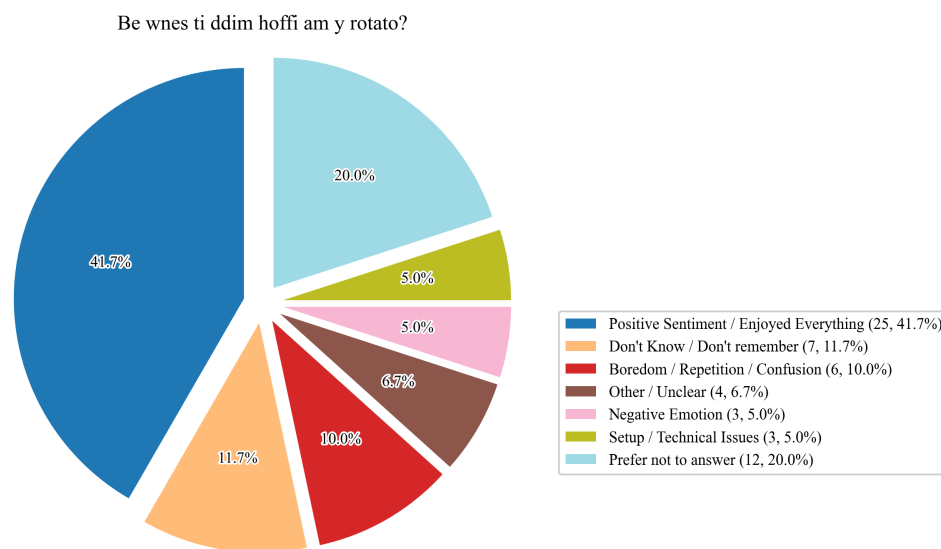


FIGURE 5.19: Responses for “What didn’t you like about the Rotato?”

Overall, 25 student responses were positive in nature, consisting either of saying there was nothing they did not enjoy about the activity or that they enjoyed it all, e.g. *“dim byd”*

Translation: “Nothing”

(Year 4, School E)

“naeth fi hoffi bob dim ”

Translation: “I enjoyed everything”

(Year 6, School C)

TABLE 5.22: Summary of the thematic categories used to analyse the responses for the question ‘What didn’t you like about the Rotato?’. The number of responses which fall into each category are listed along with its percentage. PNTA responses were excluded.

Thematic Category	n	(%)
Positive Sentiment	25	(52%)
Don’t Remember/Don’t Know	7	(15%)
Boredom/Repetition/Confusion	6	(13%)
Negative Emotion	3	(6%)
Setup/Technical Issues	3	(6%)
Other/Unclear	4	(8%)
Total	48	(100%)

Given that this is the largest category of responses this is very positive, albeit not too helpful when considering what changes could be made to improve the activity. Comparing these responses with the school year of the students, we see that there are 5 in Year 4 (28% of all Year 4 respondents), 5 in Year 5 (28% of all Year 5 respondents), and 15 in Year 6 (46% of all Year 6 respondents), suggesting that this sentiment is most popular amongst students in Year 6, but is shared to a lesser extent with other years. This highlights once again that the activity’s target year is older students.

6 students cited that they found the activity boring, repetitive, or confusing, e.g.

“un waith roedd o wedi mynd o gumpas roedd yr run un peth yn digwydd eto”

Translation: “Once it had gone around the same thing happened again” (Year 6, School E)

“edrych cynfusing [sic]”

Translation: “looks confusing” (Year 6, School C)

“oedd yr vidio [sic] yn boring”

Translation: “The video was boring” (Year 5, School D)

“basic”

(Year 4, School E)

This is a potential negative aspect of the activity (i.e. it can be repetitive and seem mundane and boring) but does represent the real-world of scientific research - it takes time and patience to get the desired results. Students finding the activities ‘boring’ is something the Comet Chasers’ programme aims to avoid as much as possible, given that the main aim is for students to enjoy the Rotato activity and, more broadly, enjoy science. It is understandable that students may feel this way, as the activity by its nature is repetitive³ and if the students are not actively thinking about how the lightcurve will look like or why what is being seen is happening, it can seem boring. During class workshops, this may be highlighted due to different activities being conducted at the same time, some of which the students may think look more interesting/exciting than the Rotato.

A way to mitigate this boredom would be to involve the entire class in the same experiment, to avoid additional distractions for the students. Another issue has been that teachers have not been interacting with the activities themselves or not monitoring the class to check if any students are struggling or misbehaving. Often teachers have sat back and not interacted with their students during the workshop, or left the classroom entirely - this adds additional challenges for the deliverer of the workshop, especially as most of these workshops were conducted solo. When teachers have helped students and investigated the activity at the same time, a marked difference in the behaviour and responsiveness of the class was noticed - they are more likely to experiment in a structured manner and seem to gain a better understanding of the core concepts behind the activity.

The ‘confusing’ aspect mentioned by some students is something that clearly needs a solution. The software used is sophisticated with numerous different abilities, with a simplified version being used during these workshops to limit the options/buttons students have access to. More discussion about the software is found in sections [5.3.2.6](#) and [5.3.2.7](#).

³Literally repetitive when waiting for the lightcurve to be produced!

While many respondents had positive responses to this question, saying that there was nothing they disliked, others did mention how the activity was repetitive or that they had had issues using the software or equipment. Students cited that the activity “Looks confusing” and another stating that it was repetitive.

5.3.2.5 Aid Understanding

Did the Rotato help you understand how astronomers understand comets? (Wnaeth y Rotato helpu ti deallt sut mae seryddwyr yn ddeall comedau?)

TABLE 5.23: Summary of responses for the question ‘Did the Rotato help you understand how astronomers understand comets?’.

Response	n	(%)
Yes	33	(55%)
No	3	(5%)
Not sure/ PNTA	24	(40%)
Total	60	(100%)

Wnaeth y 'rotato' helpu ti deallt sut mae seryddwyr yn ddeall comedau?

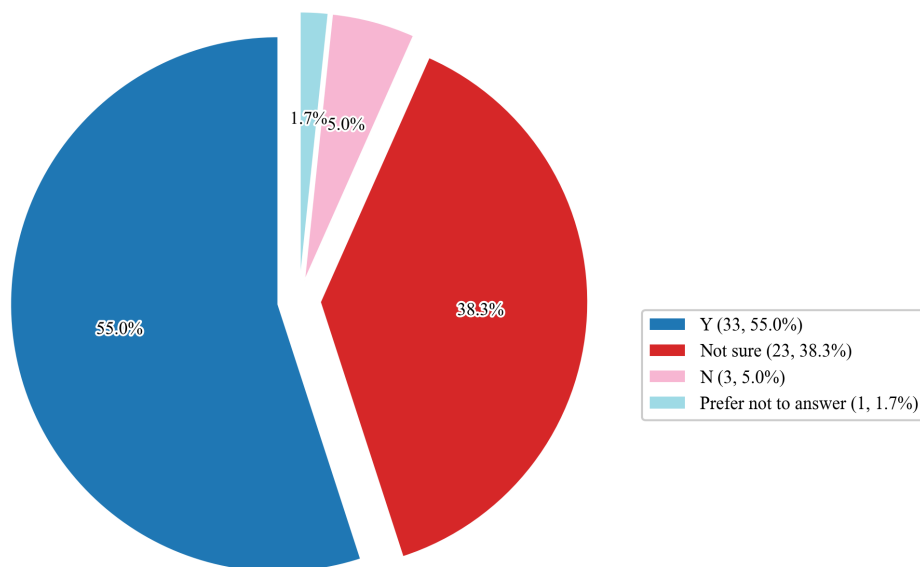


FIGURE 5.20: Responses to “Did the Rotato help you understand how astronomers understand comets?”

The majority of respondents who took part in the activity said that it did help them understand how astronomers investigate comets, with only a small number saying ‘No’, and a large section saying they were ‘Not sure’ or opted to not respond. Even when combining those who said ‘No’ and ‘Not sure’, the ‘Yes’ category is still 10% greater. This is a good indication that the experiment is able to explain a nebulous and difficult-to-grasp concept. Although, if those who responded with ‘[PNTA](#)’ or ‘not sure’ didn’t believe it helped their understanding, this is a problem. The next phases of workshops must further emphasise the link between the activity and real rotational lightcurve analysis of asteroids/comets.

It is important to bare in mind that students may think this is the ‘correct’ answer we expect, and given the small sample size, this must be taken critically.

5.3.2.6 Ease of Use of Software

Was the Rotato software on the computer easy to use?

(Oedd y meddalwedd Rotato ar y cyfrifiadur yn hawdd i ddefnyddio?)

Similar to the responses in section 5.3.2.5, the majority (63%) of students found the Rotato software easy to use. This is a very positive result, as without ‘easy-to-use’ software to pair with the experiment, it becomes far more difficult for the students to focus on learning about the concepts rather than just learning how to use the software.

TABLE 5.24: Summary of the thematic categories used to analyse the responses for the question ‘Was the Rotato software on the computer easy to use?’. The number of responses which fall into each category are listed along with its percentage.

Response	n	(%)
Yes	38	(63%)
No	3	(5%)
Not sure/ PNTA	19	(32%)
Total	60	(100%)

Oedd y meddalwedd (software) rotato ar y cyfrifiadur yn hawdd i ddefnyddio?

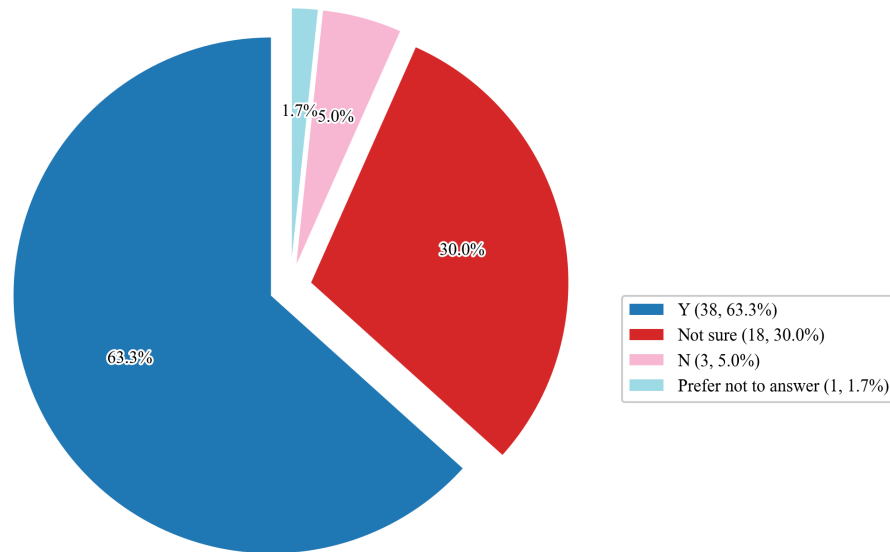


FIGURE 5.21: Responses to “Was the Rotato software on the computer easy to use?”

Despite a positive response, there is a large proportion of students who selected ‘Not sure’ (all but one of those listed in tab. 5.24). Assuming all these respondents either did not think the software was easy to use, or found some parts easy but some difficult, more must be done to ensure that the software is more accessible. As previously mentioned, the focus of the activity should be on the concepts rather than merely operating the software. Proposed solutions to how to improve the software are discussed in section 5.3.2.7.

5.3.2.7 Issues with Software

*What didn’t you like, or find difficult, with the Rotato software on the computer?
(Be wnes ti ddim hoffi, neu ffeindio’n anodd, gyda’r meddalwedd Rotato ar y cyfrifiadur?)*

This question aimed to address any uncertainties or issues students may have felt when using the software and answering the question in section 5.3.2.6. It will highlight what does not work well with the software, in addition to major

issues which may hinder students' learning/enjoyment. It is imperative that the software is easy to use, to ensure that the focus of the activity is on the science.

The three students who said they did not find the software easy to use stated:

“trio dallt [sic] yr crome books”

Translation: “Try to understand the chrome books” (Year 5, School C)

“Darllen y light scores.”

Translation: “Reading the light scores” (Year 6, School C)

“dwi ddim yn gwybod”

Translation: “I don’t know” (Year 6, School C)

Unfortunately, two of these responses are not too helpful, so it is not easy to discern what specifically make the software difficult for these students to use. However, the response of struggling to read the ‘light score’ is a very valuable suggestion. The values on the plot axes are small and can be difficult to read from a distance - these values can be enlarged and potentially could have the value shown when the cursor is over the line to ease this issue. This has been adapted in preparation for the next phase of workshops.

TABLE 5.25: Summary of the thematic categories used to analyse the responses for the question ‘What didn’t you like, or find difficult, with the Rotato software on the computer?’. The number of responses which fall into each category are listed along with its percentage.

Thematic Category	n	(%)
Positive Sentiment	24	(40%)
Software Issues	5	(8%)
Equipment Issues	3	(5%)
Negative Emotion	2	(3%)
Other/Unclear	5	(8%)
PNTA/Don’t remember	21	(35%)
Total	60	(100%)

Overall, 40% of respondents mentioned that they did not have issues with the software, with students saying they found it easy or that they did not find any aspect of the software difficult.

Be wnes ti ddim hoffi, neu ffeindio'n anodd, gyda'r meddalwedd (software) rotato ar y cyfrifiadur?

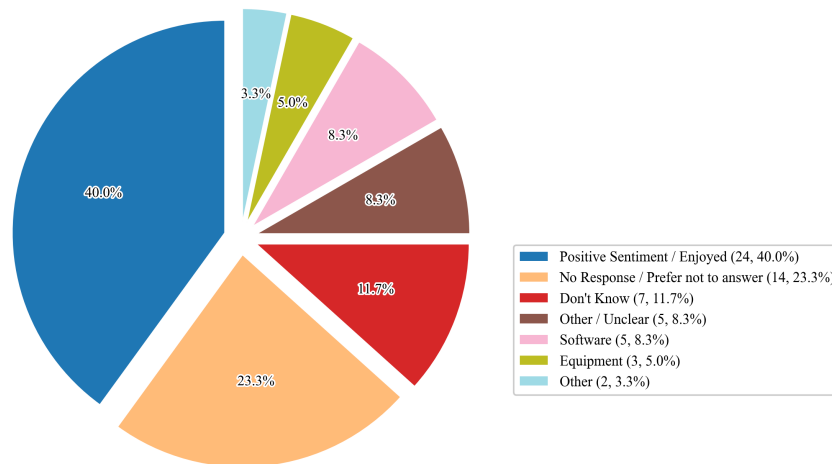


FIGURE 5.22: Responses to “What didn’t you like, or find difficult, with the Rotato software on the computer?”

“dim byd”

Translation: “Nothing”

(Year 4, School E)

“oedd pob dim yn hawdd”

Translation: “Everything was easy”

(Year 6, School C)

To have a large proportion of respondents with positive responses towards the software is very positive and suggests that there are no major issues or challenges.

Of those who did have issues with the software, 5 responses were relating to the software, 3 relating to the equipment, and 2 expressed general negative emotions.

The issues relating to the software included: *“Darllen y light scores.”*

Translation: “Reading the light scores”

(Year 6, School C)

and more generally, *“y meddalwedd”*

Translation: “The software”

(Year 6, School D)

As mentioned in section 5.3.2.6, the values on the graph are a little small and it would help the user if they were larger (or with an option for larger text). Other

students noted similar issues with reading the plot. External factors also displeased the students, with external light affecting the students' measurements.

Overall, many respondents mentioned they did not have difficulties or dislikes about the Rotato software. Some students cited issues relating directly to the software, like text size and ease of use - these issues will be ironed out in later versions of the programme. Further specific questioning on the Rotato software is required to better highlight consistent problems. Changes have been made to the software based on these responses, although it has yet to be retested with new students. Changes include:

- Increase size of light intensity values on y-axis.
- Increase size for all text.
- Mouse position shows intensity value.

5.3.3 Evaluation of Infrared Cameras activity

Summary of [IR](#) cameras activity can be read in sect. [2.4.1.1](#).

5.3.3.1 Enjoyment

Did you enjoy using the [IR](#) cameras?

(Wnes di mwynhau defnyddio'r camerâu IG?)

Students seemed to thoroughly enjoy using the [IR](#) cameras given each statistical analyses highly rates the responses. Over half of respondents ranked their enjoyment of the activity as a 5, giving a weighted average of 4.19 and [NPS](#) of 64%.

Assessing the ranking based on the respondent's year group, we see that Year 4 students ranked the activity the highest, with a weighted average of 4.28 and [NPS](#) 66.7, closely followed by Year 6 students (weighted average of 4.16, [NPS](#)

TABLE 5.26: Student responses to the question: “Did you enjoy using the IR cameras?” Responses are ranked from 1 (dislike) to 5 (love). This question aimed to assess students’ overall feelings about the IR cameras activity.

Ranking	Year 4	Year 5	Year 6	No response	Total
1	3 (17%)	1 (6%)	2 (7%)	0 (0%)	6 (8%)
2	0 (0%)	2 (11%)	1 (3%)	0 (0%)	3 (4%)
3	0 (0%)	2 (11%)	4 (12%)	0 (0%)	6 (8%)
4	1 (6%)	4 (22%)	8 (24%)	0 (0%)	13 (17%)
5	14 (78%)	8 (44%)	17 (52%)	5 (83%)	44 (59%)
No ranking	0 (0%)	1 (6%)	1 (3%)	1 (17%)	3 (4%)
Total	18 (24%)	18 (24%)	33 (44%)	6 (8%)	75 (100%)
Weighted average	4.28	3.94	4.16	5	4.19
Median	5	4	5	5	5
Mode	5	5	5	5	5
NPS	66.7%	49.9%	65.7%	83.3%	64.0%

of 65.7%). This activity has the opposite issue as mentioned in section 5.3.2.1, younger students enjoy this activity more than older students, possibly due to the interactiveness and exploring their classroom with the cameras. Again, contrasting with the Rotato experiment, this activity does not take as much sustained and challenging thought to discover how the camera works and what it shows - this results in a faster payoff in the learning process, meaning the students may have more time to ‘mess around’ with the equipment. Note: when analysing these results, the group which did not specify their school year were not taken into account, but were included in the table for completeness. A Kruskal-Wallis test found no statistically significant differences in responses to this question between year groups ($H(2) = 2.41$, $p = 0.299$).

Comparing the responses from this activity with the Rotato (section 5.3.2.1) shows that students ranked the IR cameras activity higher than the Rotato, both as a whole and each year group. The overall weighted average is 0.46 greater for IR cameras activity, and the NPS is 18.3% higher. This is a fairly substantial increase in ranking, implying that this activity is more appropriate for students of all year groups surveyed, but appeals to younger students more than for the Rotato.

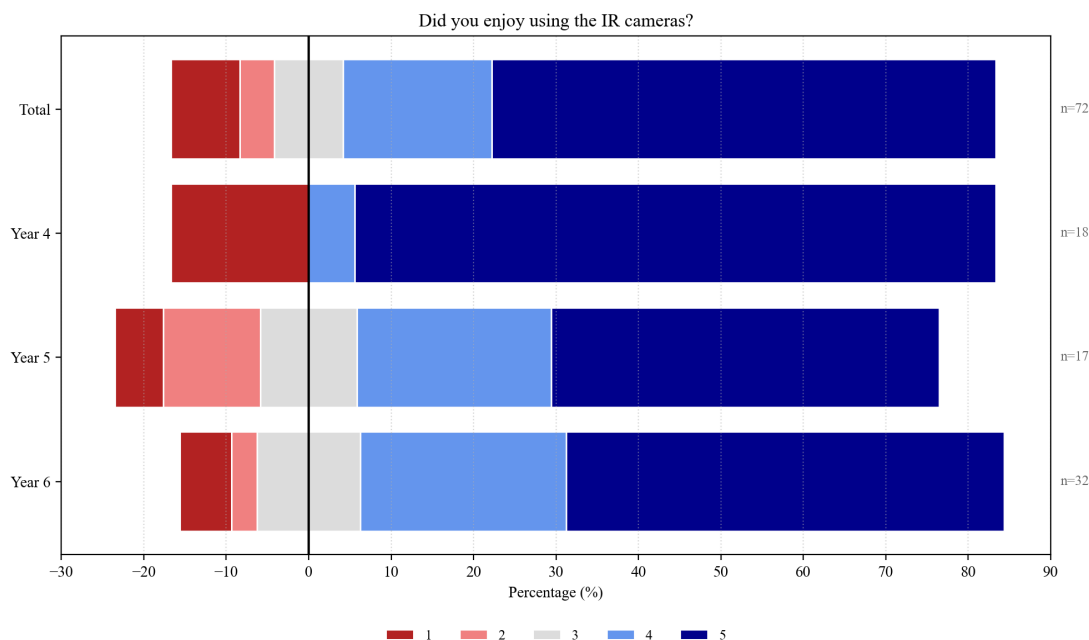


FIGURE 5.23: Diverging stacked bar chart showing the total proportions of responses to the survey question: “Did you enjoy using the IR cameras?”, as well as the distribution broken down by year group. Bars are centred on a neutral midpoint to highlight positive and negative response patterns.

Focussing on the IR cameras for younger students may improve the programme as it would better engage the younger students.

Respondents generally enjoyed the IR cameras activities, with a weighted average enjoyment ranking of 4.19 out of 5 and Net Promoter Score of 64.0%. Students in Year 4 ranked their enjoyment higher than those in Years 5 and 6 suggesting the activity may be best suited for younger students.

5.3.3.2 Learning Aspects

What did you learn from using the IR cameras?

(Be wnes ti dysgu wrth ddefnyddio'r camerâu IG?)

Like in section 5.3.2.2, this section aims to see what retains in the students' mind following the workshop.

TABLE 5.27: Summary of the thematic categories used to analyse the responses for the question ‘What did you learn from using the IR cameras?’. The number of responses which fall into each category are listed along with its percentage. PNTA responses were excluded.

Thematic Category	n	(%)
Heat and Temperature Concepts	14	(22%)
Colour and Visual Perceptions	10	(16%)
Don’t Know/Don’t Remember	10	(16%)
Observations of People	8	(13%)
Thermal Camera Use	7	(11%)
Negative Emotion	5	(8%)
UV Beads	2	(3%)
Other/Unclear	8	(13%)
Total	64	(100%)

Students’ responses were broad with some mentioning general observations made with using the cameras, some touched on how people looked through the cameras, and some saying they learnt about how the camera works. The largest category was ‘Heat and Temperature Concepts’, a fairly broad category in of itself, students mentioned different items they tested during the activity, or explaining the general use of the IR camera.

“Mae o yn canfod yr tymheredd.”

Translation: “It detects the temperature” (Year 6, School D)

“gwres pethau ac syt i dallt o”

Translation: “Heat of things and how to understand them” (Year 4, School E)

While these responses are a little vague, it is good to see that students did learn how heat behaves. It would be more useful to have had the respondents go into further detail about what they specifically learnt, although this may be due to the phrasing of the question. Adding additional information to ask what exactly they learnt would hopefully ensure that the responses are specific.

Numerous students touched on how they are able to use the cameras to see colours that our eyes cannot, categorised in the ‘Colour and Visual Perceptions’ group.

“wahanol lliwiau da ni methu gweld”

Translation: “Different colours we can’t see” (Year 4, School H)

“gweld gwahanol lliwiau”

Translation: “See different colours” (Year 4, School H)

This is a very important concept for this activity. During the workshop, IR light is described as a different colour that we cannot see - this can be seen in the responses by the students. While a simplified version of the science, it does express to students that IR is a form of light outside of the visual spectrum. This concept is difficult to grasp when you have no awareness of what wavelength is, so it is positive to see that numerous students were able to gain this knowledge. It is important to note that most students from school F had responses which fell in this category suggesting they may have completed it as a class, or that the teacher had given suggestions on what to say.

Students noted they learnt how IR cameras are able to detect heat, and view a different ‘colour’ not detectable by human eyes.

5.3.3.3 Favourite part

What was your favourite part of the IR cameras?

(Be oedd y rhan orau o ddefnyddio’r camerâu IG?)

The two largest categories were students learning about body temperature with 14 responses (36%), and general observations/investigations into temperatures of objects with 12 responses (22%).

Students who mentioned body temperature touched mainly on either how people were warm, how they appeared through the camera, or how body heat interacts with other objects.

“edrych a’r bobl gyda sbectol oherwyrdd roedd nhw’n edrych fel penglog”

Translation: “Looking at people with glasses because they looked like a skull”

(Year 6, School C)

TABLE 5.28: Summary of the thematic categories used to analyse the responses for the question ‘What was your favourite part of the IR cameras?’. The number of responses which fall into each category are listed along with its percentage. PNTA responses were excluded.

Thematic Category	n	(%)
Body Temperature	14	(36%)
Temperature Observations	12	(22%)
Don't Know/Don't Remember	11	(20%)
Positive Sentiment	4	(7%)
Thermal Camera Use	3	(6%)
Negative Emotion	3	(6%)
UV Beads	3	(6%)
Other	4	(7%)
Total	54	(100%)

Be oedd y rhan orau o ddefnyddio'r camerau IG?

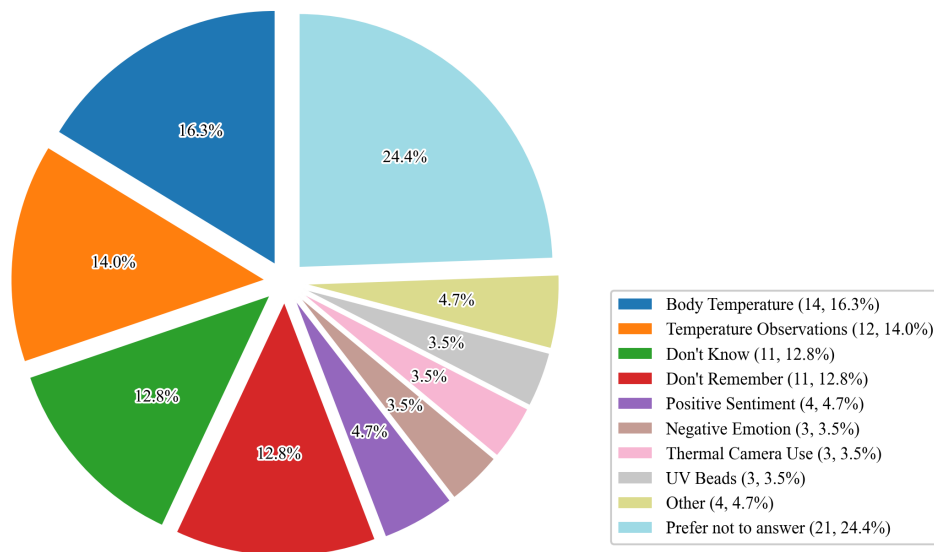


FIGURE 5.24: Responses to “What was your favourite part of the IR cameras?”

“gweld os mae pobl yn boeth neu ddim yn boeth”

Translation: “See if people are hot or not hot”

(Year 5, School D)

“Gweld ein finger prints pan oedd ni yn rhoi ein dwylo ar y burdd.”

Translation: “See our finger prints when we put our hands on the table.” (Year 6, School C)

It is interesting to hear that observing people using the IR cameras was the most exciting aspect for numerous students. While students should know at this age that most animals emit heat, the extent of this may not be apparent to them until they are able to use the camera to compare their classmates with a cold Welsh classroom in the winter. There is a novelty in seeing people through this unique lens, where students may have only seen something similar in the form of night-vision goggles in films and TV. Comparing how skin looks through the camera with hair or glasses is interesting, highlighting both the aid that hair gives to insulate the body and how glasses are opaque in the IR spectrum.

Observing the body's interactions with other objects and the transferring of heat would also be a novel experience to students. A hand on the table does not transfer enough heat to be visible to the naked eye, nor to the touch (apart from in extreme situations), so seeing that an imprint is visible using the IR-band is an almost magical experience to many students.

Students whose responses fell into the 'Temperature Observations' category touched on general mentions of how warm/cold some things are, and mentioning specific parts of the activity.

“cael gweld beth oedd yr pethau poethafac [sic] oeraf”

Translation: “Seeing what were the warmest and coldest things” (Year 6, School D)

“i gweld os mae rywbeth yn poeth neu oer heb cyffwrdd”

Translation: “To see if something is hot or cold without touching” (Year 6, School D)

“Gweld y dwr oer a boeth”

Translation: “Seeing the cold and hot water” (Year 6, School C)

As students were free to investigate their classroom with the IR cameras, it is no surprise that many students cited, quite broadly, they enjoyed comparing different objects' temperatures. A couple of responses specifically mentioned investigating the hot and cold water bottles - this was part of the activity where

students were first asked to visually guess which of two bottles contained very hot water followed by using the [IR](#) camera.

5.3.3.4 Dislikes

What didn't you like about the [IR](#) cameras?

(Be wnes ti ddim hoffi am y camerâu IG?)

TABLE 5.29: Summary of the thematic categories used to analyse the responses for the question ‘What didn’t you like about the [IR](#) cameras?’. The number of responses which fall into each category are listed along with its percentage. [PNTA](#) responses were excluded.

Thematic Category	n	(%)
Positive Sentiment	24	(53%)
Don't Know/Don't Remember	6	(13%)
Camera Issues	4	(9%)
Sharing Cameras	4	(9%)
Negative Emotion	3	(7%)
Other	4	(9%)
Total	45	(100%)

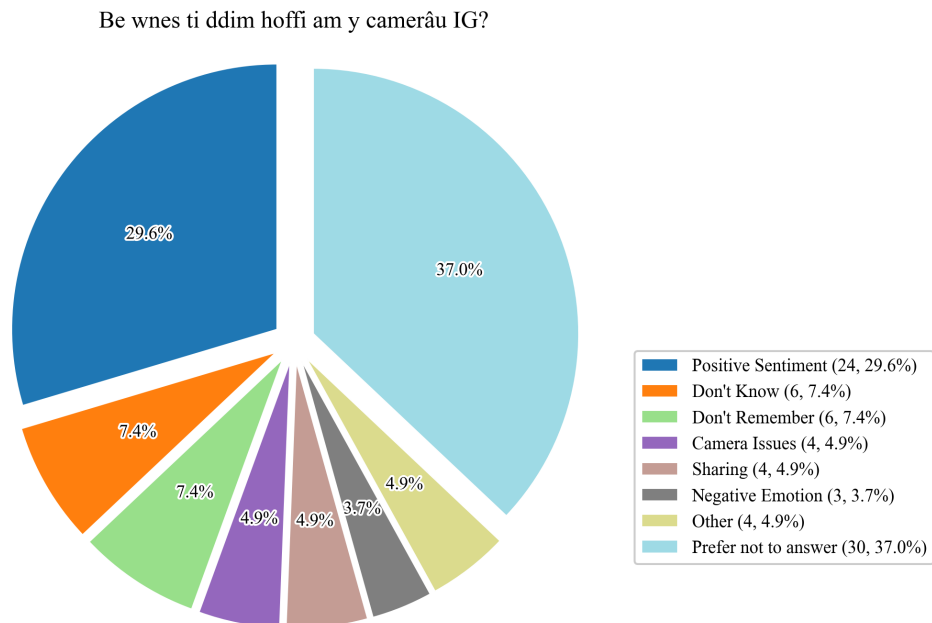


FIGURE 5.25: Responses to “What didn’t you like about the [IR](#) cameras?”

Other than ‘PNTA’, the largest category was of a positive sentiment. Most of the 24 responses in this category consisted of ‘Nothing’ meaning the students did not dislike any part of the activity. This is very positive and suggesting that many students enjoyed the activity.

“dim byd mae y beth hwn yn da”

Translation: “Nothing this thing is good” (Year 6, School G)

“o ni hoffi bob dim”

Translation: “I liked everything” (Year 4, School E)

Of those who did specify aspects they disliked from the activity, they noted camera issues or sharing the cameras. Camera issues consisted,

“oedd yr buttonss [sic] yn anodd i defnyddio”

Translation: “The buttons were difficult to use” (Year 5, School D)

“oedd nhw drwm”

Translation: “They were heavy” (Year 6, School E)

These issues are valid and could be an issue for students, although we do what we can to mitigate these issues. For example, students do not need to press any buttons on the camera, it is already set up for them and they just need to ‘point and shoot’. The cameras being heavy is a problem for smaller students, it is therefore very important that the students share the cameras and help other students who may be struggling. This would be a useful fact to state at the beginning of the workshop to ensure that all students are able to take part and enjoy the activity as much as possible.

Students’ responses that related to sharing involved, *“Oedd na ond dau ac oedd rhai pobl ddim wedi cael turn gyda nhw.”*

Translation: “There were only two and some people didn’t have a turn with them.”
(Year 6, School C)

“oedd pawb ddim di gael tro”

Translation: “Everyone didn’t have a turn” (Year 6, School C)

This is a major issue as the programme aims to ensure that everyone is included and available to take part in the workshops. It is important to note that all respondents who were in this category were from the same school suggesting this may have been more of an issue during one workshop. Again, reiterating that the students must share the cameras and ensure that everyone has an opportunity to operate the camera could help along with keeping an eye on which students are using the cameras for a long time.

5.3.4 Meteorites Evaluation

Summary of meteorite handling activity can be read in sect. [2.4.1.2](#).

5.3.4.1 Enjoyment

Did you enjoy holding and experimenting on the meteorites?

(Wnes ti mwynhau gafael ac arbrofi ar y meteorynnau?)

Students viewed the meteorite activity very positively, albeit slightly less than in section [5.3.3.3](#). Over half the respondents ranked their enjoyment of meteorite handling a 5, with weighted average of 4.06 and [NPS](#) of 56.0%, suggesting an enjoyment of the activity.

All year groups were somewhat regular in their enjoyment of the workshop overall, with a weighted average from 3.97 to 4.06, and [NPS](#) ranging from 42.4% to 55.5% for each individual year. A Kruskal-Wallis test found no statistically significant differences in responses to this question between year groups ($H(2) = 0.38$, $p = 0.826$). This activity has a broad appeal for the three years surveyed, with the younger students ranking the activity marginally higher than Year 6 respondents. This is expected given the exciting and novel experience of handling meteorites, even if students have held a meteorite before, it would likely still evoke an interest in the activity. Using the meteorites as a vehicle to reignite

TABLE 5.30: Student responses to the question: “Did you enjoy holding and experimenting on the meteorites?”. Responses are ranked from 1 (dislike) to 5 (love). This question aimed to assess students’ overall feelings about the meteorite handling activity.

Ranking	Year 4	Year 5	Year 6	No response	Total
1	2 (11%)	1 (6%)	3 (9%)	0 (0%)	6 (8%)
2	1 (6%)	1 (6%)	2 (6%)	0 (0%)	4 (5%)
3	1 (6%)	3 (17%)	6 (9%)	0 (0%)	10 (13%)
4	3 (17%)	3 (17%)	6 (9%)	0 (0%)	12 (16%)
5	10 (56%)	9 (50%)	16 (49%)	5 (83%)	40 (53%)
No ranking	1 (6%)	1 (6%)	0 (0%)	1 (17%)	3 (4%)
Total	18 (24%)	18 (24%)	33 (44%)	6 (8%)	75 (100%)
Weighted average	4.06	4.06	3.97	5.0	4.06
Median	5	5	5	5	5
Mode	5	5	5	5	5
NPS	55.6%	55.5%	42.4%	83.3%	56.0%

students’ interest in a workshop would be useful as it appears it would be well received by all students.

5.3.4.2 Learning Aspects

What did you learn by doing experiments on the meteorites?

(Be wnes ti dysgu wrth gwneud arbrofion ar y meteorynnau?)

TABLE 5.31: Summary of the thematic categories used to analyse the responses for the question ‘What did you learn by doing experiments on the meteorites?’. The number of responses which fall into each category are listed along with its percentage. [PNTA](#) responses were excluded.

Thematic Category	n	(%)
Age	16	(31%)
Don’t Know/Don’t Remember	9	(17%)
Weight	8	(15%)
Magnetism	6	(12%)
Origin	5	(10%)
Value	2	(4%)
Other	6	(12%)
Total	52	(100%)

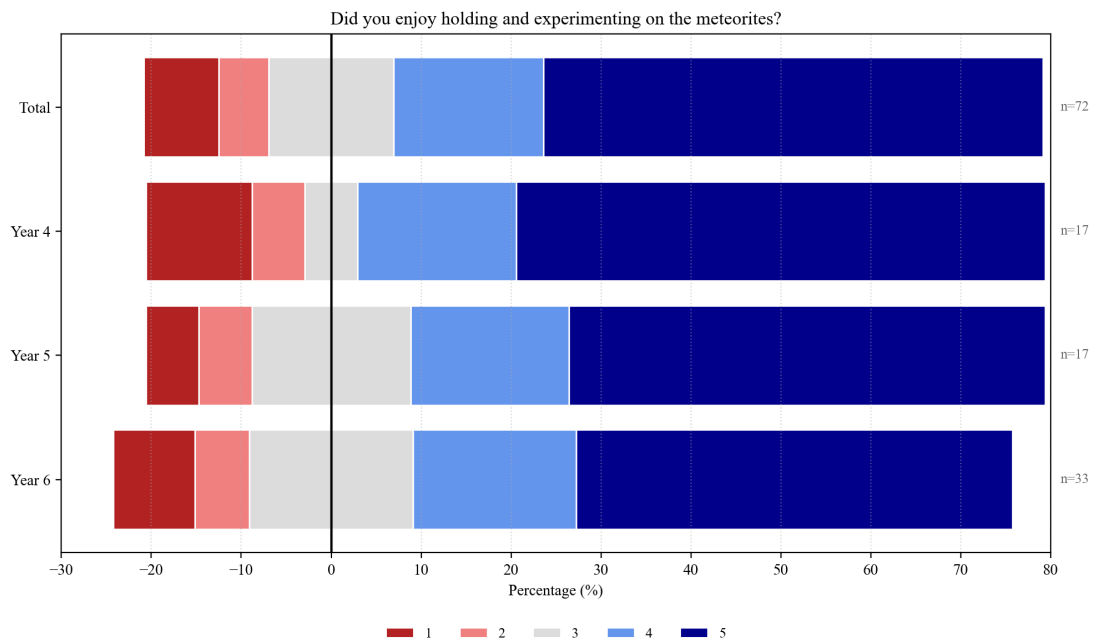


FIGURE 5.26: Diverging stacked bar chart showing the total proportions of responses to the survey question: “Did you enjoy holding and experimenting on the meteorites?”, as well as the distribution broken down by year group. Bars are centered on a neutral midpoint to highlight positive and negative response patterns.

31% of respondents mentioned the age of some of the meteorites they were handling when responding to this question. This is often the greatest ‘wow-factor’ fact when conducting outreach with the meteorite samples. While many students could not remember the age of the samples specifically, some did get very close, and most were aware of how ancient these objects are.

“Mae nhw 4.5 billiwn oed”

Translation: “They’re 4.5 billion years old” (Year 4, School H)

“bod yna cerig lot hyn na fi”

Translation: “There are rocks lots older than me” (Year 5, School E)

“bod metiorau gallu bod fwy hen na y byd”

Translation: “That meteorites can be more old than the world” (Year 6, School C)

It is impressive that a student in Year 4 could remember the age of the meteorites. During this activity, it is reiterated how old, unbelievably old, these objects are therefore it is good to see that this does stay in students' minds.

Students were often surprised by the weight of the meteorites, especially when holding both the chondrite and ferrous meteorites at the same time. 8 responses touched on this, with some also mentioning the fact that the ferrous meteorite is magnetic - a part of the experimenting process during the activity.

5.3.4.3 Favourite Part

What was your favourite part of the meteorites?

(Be oedd y rhan orau o'r meteorynnau?)

TABLE 5.32: Summary of the thematic categories used to analyse the responses for the question 'What was your favourite part of the meteorites?'. The number of responses which fall into each category are listed along with its percentage. [PNTA](#) responses were excluded.

Thematic Category	n	(%)
Handling	17	(31%)
Don't Know/Don't Remember	8	(15%)
Magnetism	7	(13%)
Age	6	(11%)
Positive Sentiment	4	(7%)
Weight	4	(7%)
Observations	2	(4%)
Other	6	(11%)
Total	54	(100%)

Handling the meteorites were the most popular category for the respondents' favourite aspect of the workshop.

“cael gafel y cerig”

Translation: “Get to hold the rocks”

(Year 5, School C)

“gafal nhw”

Translation: “Holding them”

(Year 4, School E)

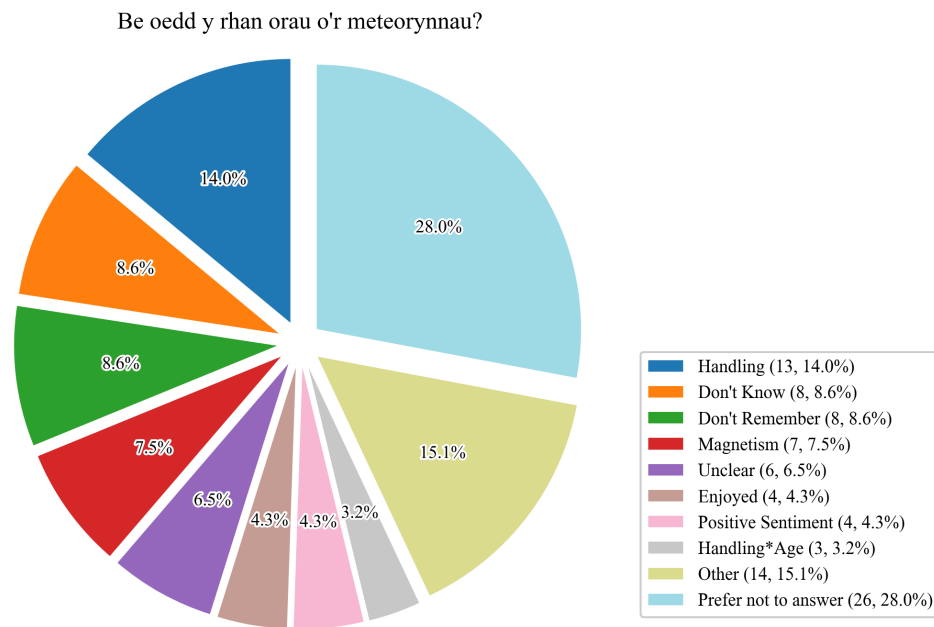


FIGURE 5.27: Responses to “What was your favourite part of the meteorites?”

This is unsurprising as it is likely an entirely novel experience for the students - potentially the first time the students would have knowingly touched something that has come from space. This makes astronomy and space something more tangible that the students can better understand, rather than simply learning about space from a textbook or science lesson. Relating to this category is ‘Weight’, where the students were impressed or surprised by the weight of the sample.

Again, students mention they liked that the samples were so old, with 6 responses touching on this. Investigating if a sample is magnetic was part of the activity, and was cited by 7 students that this is what they enjoyed the most.

5.3.4.4 Dislikes

What didn't you like about the meteorites?

(Be nes di ddim hoffi am y meterorynnau?)

TABLE 5.33: Summary of the thematic categories used to analyse the responses for the question ‘What didn’t you like about the meteorites?’. The number of responses which fall into each category are listed along with its percentage. PNTA responses were excluded.

Thematic Category	N (%)
Positive Sentiment	23 (50%)
Don’t Know/Don’t Remember	9 (20%)
Hygiene	3 (7%)
Negative Emotion	2 (4%)
Weight	2 (4%)
Other	7 (15%)
Total	46 (100%)

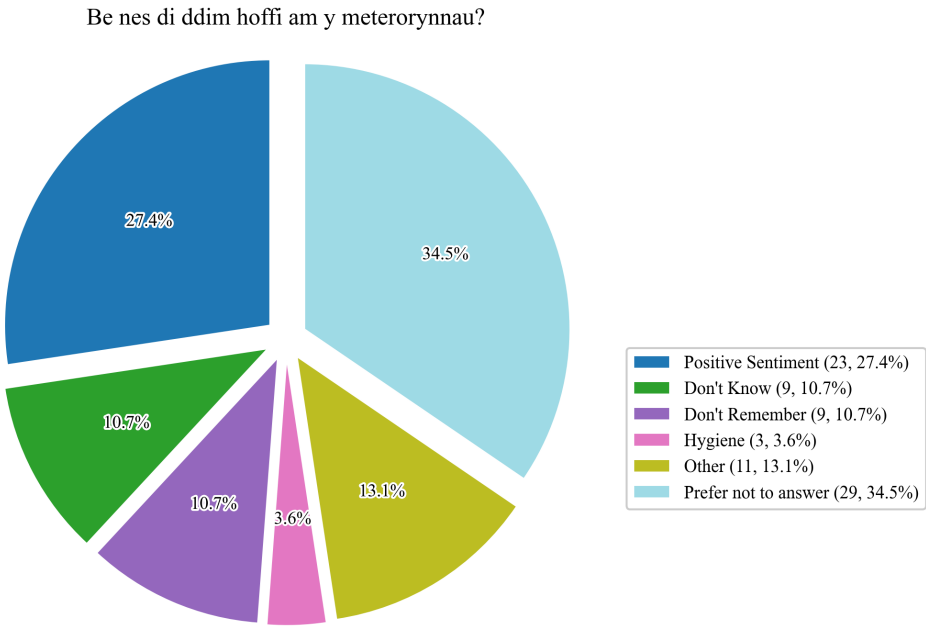


FIGURE 5.28: Responses to “What didn’t you like about the meteorites?”

50% of respondents responded to this question positively, with numerous students saying that they disliked nothing. *“mi wnes i mwynhau pobeth”*
Translation: *“I enjoyed everything”* (Year 4, School E)

“dim bud oedd yn gret”
Translation: *“Nothing it was great”* (Year 6, School D)

Similar to responses in sections 5.3.2.4 and 5.3.3.4, it is very positive to have many students have no dislikes about the activity, it does not help us to improve

this activity.

3 students mentioned that they had issues with the hygiene associated with the samples. This is valid, as they are touched by many students. Discussions should be conducted about how we could maintain good hygiene with handling the meteorites, antibacterial wipes could be used.

5.3.5 Overall Evaluation of the Workshop

5.3.5.1 Enjoyment

Did you enjoy the Comet Chasers' session? (Wnes ti mwynhau y sesiwn Cipwyr Comedau?)

This question aimed to assess the students' general enjoyment of the workshop as a whole. Pairing this question with the following questions will give an insight into what the students enjoyed and disliked the most.

TABLE 5.34: Student responses to the question: "Did you enjoy the Comet Chasers session?". Responses are ranked from 1 (dislike) to 5 (love). This question aimed to assess students' feelings about the workshop as a whole.

Ranking	Year 4	Year 5	Year 6	No response	Total
1	3 (16.7%)	0 (0.0%)	2 (6.1%)	0 (0.0%)	5 (6.7%)
2	0 (0.0%)	2 (11.1%)	0 (0.0%)	0 (0.0%)	2 (2.7%)
3	1 (5.6%)	5 (27.8%)	4 (12.1%)	0 (0.0%)	10 (13.3%)
4	1 (5.6%)	3 (16.7%)	8 (24.2%)	0 (0.0%)	12 (16.0%)
5	12 (66.7%)	5 (27.8%)	17 (51.5%)	5 (83.3%)	39 (52.0%)
No ranking	1 (5.6%)	3 (16.7%)	2 (6.1%)	1 (16.7%)	7 (9.3%)
Total	18 (24.0%)	18 (24.0%)	33 (44.0%)	6 (8.0%)	75 (100%)
WA	4.12	3.73	4.23	5.00	4.15
Median	5	4	5	5	5
Mode	5	3 and 5	5	5	5
NPS	55.6%	33.4%	69.6%	83.3%	58.6%

Overall, students enjoyed the workshop, with a weighted average of 4.15 and **NPS** of 58.6%, implying a general liking of the subject. Each individual year

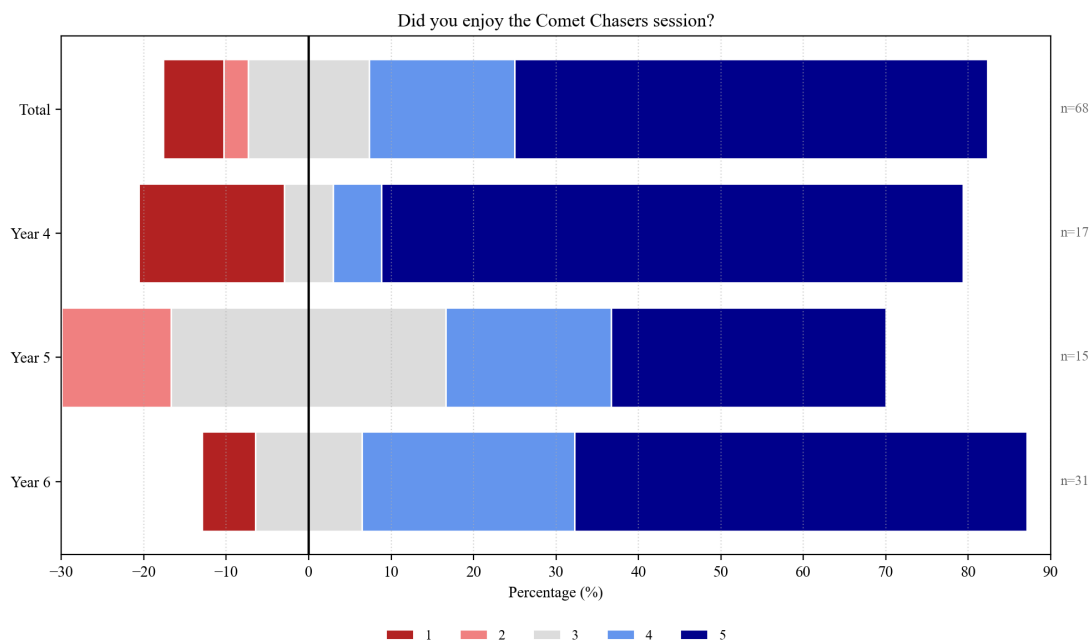


FIGURE 5.29: Diverging stacked bar chart showing the total proportions of responses to the survey question: “Did you enjoy the Comet Chasers session?”, as well as the distribution broken down by year group. Bars are centred on a neutral midpoint to highlight positive and negative response patterns.

group also enjoyed the workshop, with Year 5 students enjoying it the least. Year 6 respondents had a weighted average of 4.23 and NPS of 69.6%, and followed by Year 4 students, with a weighted average of 4.12 and NPS of 55.6%. This data suggests that the workshop is better suited towards students in Years 4 and 6, with Year 5 students not enjoying the workshop as much, though a Kruskal-Wallis test found no statistically significant differences between year groups ($H(2) = 3.40$, $p = 0.183$).

From assessing the ranking of individual activities within the workshop, it is clear why we see this difference in the school years. The activities are more catered towards either the older or younger students, leaving a gap with the students in Year 5. Despite not ranking the workshop a 1, respondents in Year 5 had a more equal distribution with the other ranks than Years 4 and 6, although the sample size is small - all other year groups have a majority of respondents who ranked the workshop a 5, clearly seen from the median and mode values.

It is important to focus on the fact that the students overwhelmingly enjoyed the workshop which is ideal as this is the main aim of the Comet Chasers programme: to intrigue and ensure students enjoy learning about science.

5.3.5.2 Favourite Activity

What did you enjoy the most from the session?

(Be wnes ti mwynhau y mwyaf o'r sesiwn?)

This question was asked to assess which activity, or aspect of an activity, the students enjoyed the most, giving us an indication of which activities are the most popular.

TABLE 5.35: Summary of the thematic categories used to analyse the responses for the question ‘What did you enjoy the most from the session?’. The number of responses which fall into each category are listed along with its percentage. [PNTA](#) responses were excluded.

Thematic Category	n	(%)
Meteorites	15	(24%)
Everything	13	(21%)
IR Cameras	9	(15%)
Rotato	5	(8%)
Comets	3	(5%)
Don't Know/Don't Remember	3	(5%)
Negative Sentiment	3	(5%)
UV Beads	2	(3%)
Learning	2	(3%)
Other	7	(11%)
Total	62	(100%)

The largest category for the respondents' most enjoyable aspect of the workshop was the meteorite activity with 15 respondents (24%) mentioning this activity.

“gweld yr cerig sydd di bod yna cyn y ddear [sic]”

Translation: “See the rocks that have been there before the Earth” (Year 6, School E)

“cael gafel y cerig [sic]”

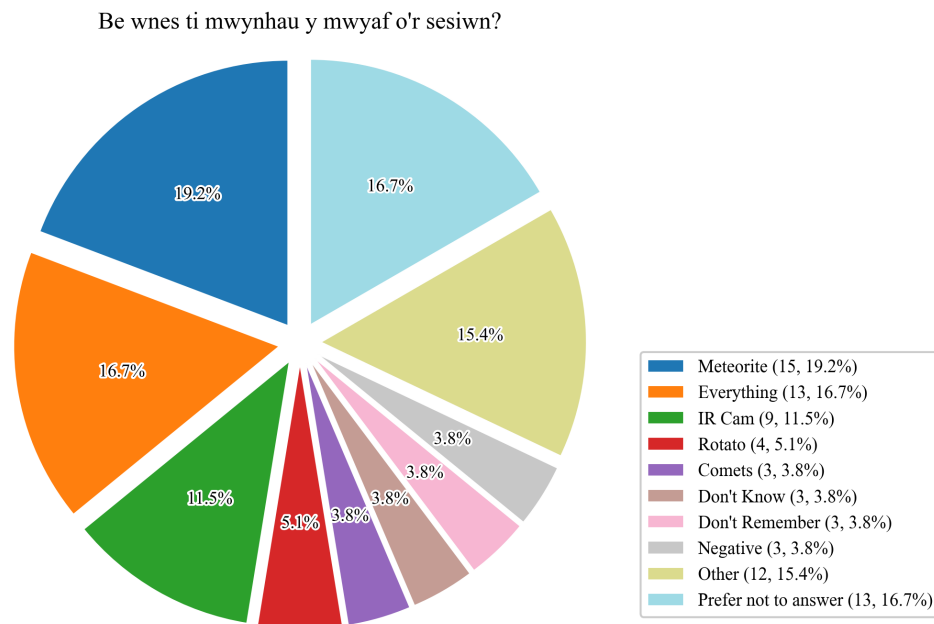


FIGURE 5.30: Responses to “What did you enjoy the most from the session?”

Translation: “Holding the rocks”

(Year 5, School C)

This activity being the most enjoyable does not line up with the rankings of the activities by respondents in sections 5.3.2.1, 5.3.3.1, and 5.3.4.1 which suggests that the IR cameras activity was the most popular. While these metrics can be compared, they are not directly associated as this question does not specify that the students must select an activity, instead asked what their favourite part of the workshop was. Additionally, the students who said they enjoyed everything about the workshop could have a preference towards the IR cameras activity.

13 respondents (21%) claimed to enjoy everything about the workshop.

“bob dim ”

Translation: “Everything”

(Year 4, School E)

“Roedd i yn hoffi bob dim”

Translation: “I liked everything”

(Year 5, School D)

Having the students enjoy every part of the workshop is the ideal situation.

These responses are backed up by their responses to the following question (section 5.3.5.3), where they answered ‘Nothing’, ‘Don’t Remember’, or opted to not answer.

5.3.5.3 Dislikes

What didn’t you like about the session?

(Be wnes ti ddim mwynhau am y sesiwn?)

This question is a place for students to specify the issues they may have encountered during the workshop. Hopefully, students are open to share aspects they disliked given the anonymous nature of the questionnaire.

TABLE 5.36: Summary of the thematic categories used to analyse the responses for the question ‘What didn’t you like about the session?’. The number of responses which fall into each category are listed along with its percentage. [PNTA](#) responses were excluded.

Thematic Category	n	(%)
Nothing	28	(64%)
Don’t Know/Don’t Remember	3	(7%)
Negative Sentiment	2	(5%)
Comets	2	(5%)
IR Cameras	2	(5%)
Meteorites	2	(5%)
Other	5	(11%)
Total	44	(100%)

Other than students who opted not to respond, the largest category of responses consisted of ‘Nothing’. 28 respondents (64%) mentioned that there wasn’t anything they disliked about the workshop as a whole.

“mi wnes mwynhau pobeth”

Translation: “I enjoyed everything”

(Year 4, School E)

“Es i mwynhau bob munud or gwers.”

Translation: “I enjoyed every minute of the lesson”

(Year 6, School D)

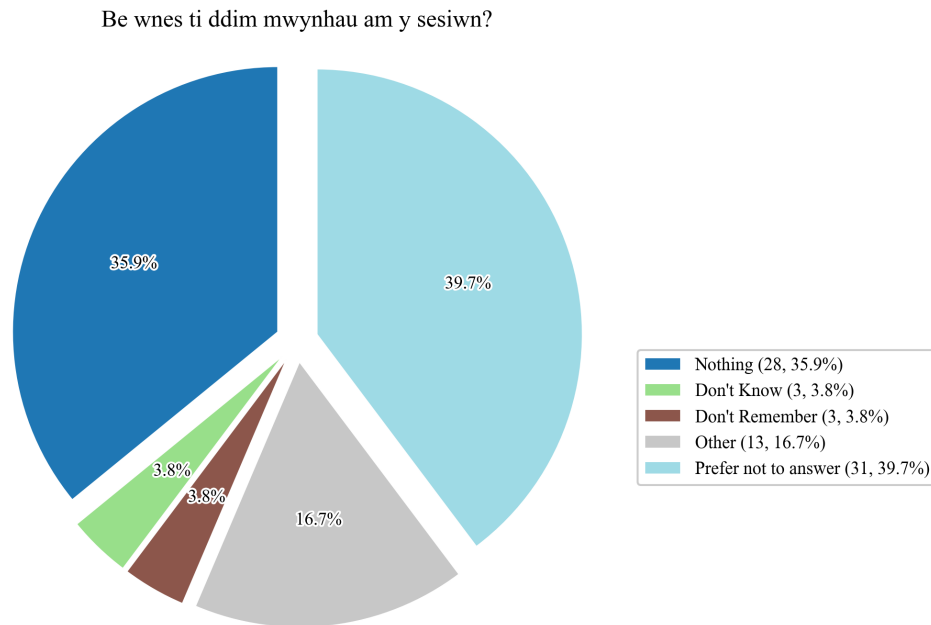


FIGURE 5.31: Responses to “What didn’t you like about the session?”

“dim byd”

Translation: “Nothing”

(Year 5, School C)

As mentioned in section 5.3.5.2, it is a very positive sign that students could not find aspects of the workshop that they disliked.

Other responses included specific activities, such as the IR cameras, meteorites, or learning about comets. It is not possible to remove these aspects from the workshop as they are the core parts.

5.3.5.4 Improvement Suggestions

How could we make Comet Chasers better?

(Sut fedra ni gwellau Cipwyr Comedau?)

This question was a direct request to be able to address any problems that stood out in the students’ minds following the workshop. Students may be more responsive to give improvements rather than stating openly what they disliked about the activities or programme as a whole.

TABLE 5.37: Summary of the thematic categories used to analyse the responses for the question ‘How could we make Comet Chasers better?’. The number of responses which fall into each category are listed along with its percentage. PNTA responses were excluded.

Thematic Category	n	(%)
Don't Know/Don't Remember	12	(26%)
Nothing	10	(21%)
More Activities	5	(11%)
More Meteorites	5	(11%)
Negative Emotion	3	(6%)
More Instruction	2	(4%)
Software Changes	2	(4%)
Other	8	(17%)
Total	47	(100%)

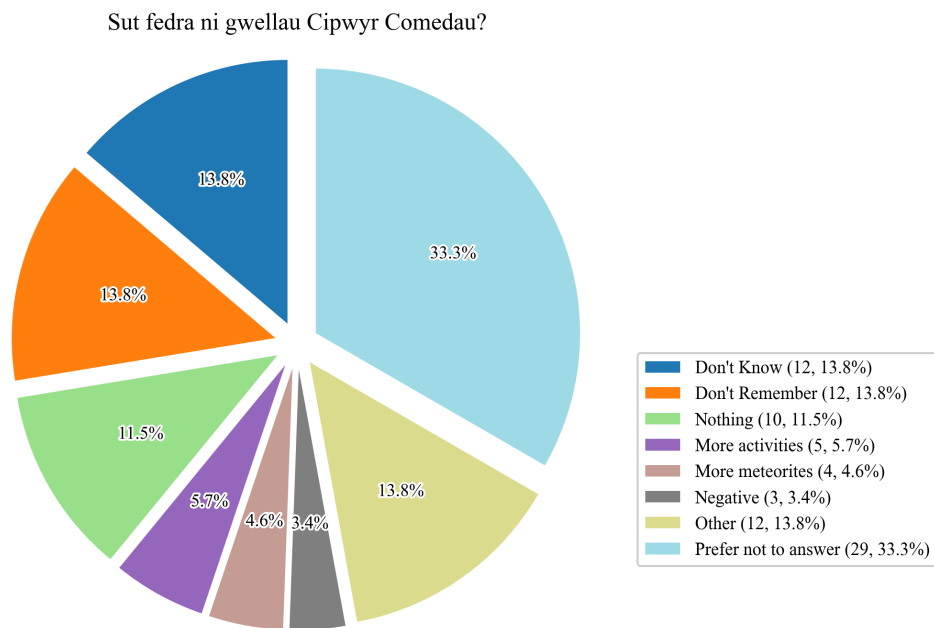


FIGURE 5.32: Responses to “How could we make Comet Chasers better?”

22 responses (48%) were very positive in their nature, consisting of saying there wasn't anything to change, or to include more activities/parts of the activity.

“dim byd”

Translation: “Nothing”

(Year 5, School D)

“gwneud mwy o gweithgareddau”

Translation: “Do more activities” (Year 6, School C)

“ella trio gael mwy o gomedau i ddod i ddangos”

Translation: “Maybe try to get more comets to bring to show” (Year 6, School G)

Without the limitation of time and availability, conducting more activities would be a welcomed change to the workshops. These responses do support the students’ desires to continue taking part in the Comet Chasers programme, more in section 5.3.5.8, and that they clearly do enjoy the workshops.

Of those who did not respond as overwhelmingly positive, others mentioned wishing further instruction with the activities.

“Eglurwch mwy”

Translation: “Explain more” (Year 5, School C)

“...ddeud ar papur beth tin neud gyder i gid or pethau”

Translation: “...say on paper what you do for all of the things” (Year 6, School C)

Students were given brief ‘how-to’ guide on how to use the Rotato equipment and software, and meteorite type identification, in addition to worksheets to guide the students throughout the activities. The worksheets for the IR cameras and meteorites activities were existing Comet Chasers and ‘Down2Earth’ material translated for Welsh language schools. Due to the Rotato being a newer developed experiment, new worksheets were created to lead the students to learn difference aspects of how light behaves and can be used by astronomers to investigate astronomical bodies. These workshops were heavily based on those created for the ‘Exoplanet Hunters’ workshop by Chemaine Barrett at Cardiff University, which uses the same equipment as the Rotato experiment.

All these resources were available for students to use and learn from, in addition to any help the deliverers can supply. For younger students, the paper instructions may not be as well received as personal help would be. Having more

people available during the workshop to aid students with any issues that might arise while they are performing the activities would be very valuable and useful for the students - they would have even more prompt help and, if enough helpers, constant help to lead the students towards the goals of the activity. Students were directed to the worksheets/how-to guides on the tables at the start of the workshop, although many did not make use of them.

Rotato software changes were also noted as an improvement to the workshop.

“gael gwell fidio quality”

Translation: “Get better quality video” (Year 6, School C)

“neud y [sic] loadio mwy fast”

Translation: “make the loading more fast” (Year 6, School D)

These are valid criticisms of the software. Students using the software have been the main trial for it, without much User Testing being conducted before these workshops. Not mentioned in the questionnaires by any respondents, the software did crash or freeze fairly regularly, which delayed the students in achieving the goals of the activity. Further vigorous testing and tweaks in the code are needed to make the software as easy to use and remove as many bugs as possible. Issues with the software are attributed to inexperience developing this type of programme - these skills were learnt while developing the software.

Overall, respondents had a positive view as to improve Comet Chasers, be that by mentioning that nothing could be done to make the programme better, or requesting more activities/meteorites. Students who have improvements for areas that the workshop lacked consisted of desiring additional explanations for concepts and activities, and improvements to the Rotato software. As mentioned in section 5.3.2.7, this feedback was used to amend the software, and to be trialled in the future.

5.3.5.5 Confusion or Issues with Activities

Was there anything you didn't understand during the session?

(Oedd yna rywbeth unes ti ddim deall yn ystod y sesiwn?)

This question is important to ask as to address any aspects of the workshop that the students may find more difficult or confusing. Students may feel unable to ask for clarification on topics, especially if their peers have already understood the activity, so asking directly in an anonymised survey is a good way to discover these issues.

TABLE 5.38: Summary of the thematic categories used to analyse the responses for the question ‘Was there anything you didn’t understand during the session?’. The number of responses which fall into each category are listed along with its percentage.

Thematic Category	n	(%)
Nothing	26	(62%)
Don't Know/Don't Remember	4	(6%)
Negative Sentiment	2	(3%)
Rotato	2	(3%)
‘Yes’	2	(3%)
Other	6	(10%)
Total	42	(100%)

Other than students who opted to not answer the question, most students said that there was nothing they did not understand. This is very positive, suggesting that the content is well explained and the activities do not introduce additional confusion for some students.

Some students did not specify what they did not understand, but simply said there were aspects that caused confusion. Two other students mentioned the Rotato exercise, with one specifying, *“syt [sic] i gweithio yr rotato”*

Translation: “How to work the rotato” (Year 6, School C)

While the Rotato equipment is already set up for the students before the workshop begins, it would be beneficial to add additional information how to operate

Oedd yna rywbeth wnes ti ddim deall yn ystod y sesiwn?

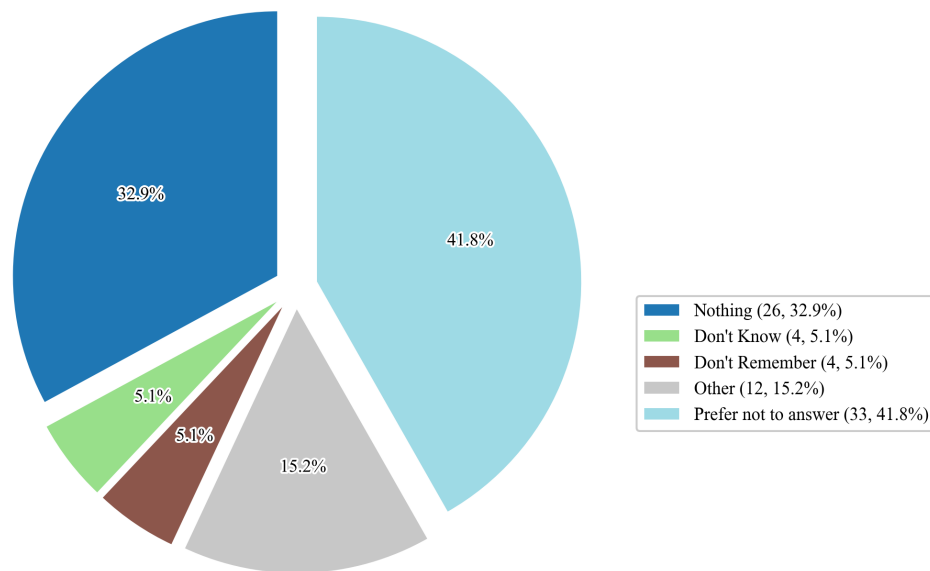


FIGURE 5.33: Responses to “Was there anything you didn’t understand during the session?”

specific parts of the equipment, such as the turntable which has a confusing set of buttons to operate.

5.3.5.6 Appeal of using Telescopes

Would you like to help Comet Chasers by using telescopes across the world to take photos of comets?

(Fysa ti yn hoffi helpu Cipwyr Comedau gan ddefnyddio telesgopau ar draws y byd i gymryd lluniau o comedau?)

This question was asked to see how many students would be interested in the most exciting prospect of the Comet Chasers programme, using the [LCO](#) network to image comets. Its aim was to quickly assess how interested and open the respondents would be to continuing with Comet Chasers’ activities thus diving further into the science.

An equal amount of respondents said either they would like to use telescopes to image comets, or that they weren’t sure. This could mean that the question was

TABLE 5.39: Summary of responses to the question ‘Would you like to help Comet Chasers by using telescopes across the world to take photos of comets?’. PNTA responses were excluded.

Response	n	(%)
Yes	31	(44%)
No	9	(13%)
Not sure	31	(44%)
Total	71	(100%)

Fysa ti yn hoffi helpu Cipwyr Comedau gan ddefnyddio telesgopau ar draws y byd i gymryd lluniau o comedau?

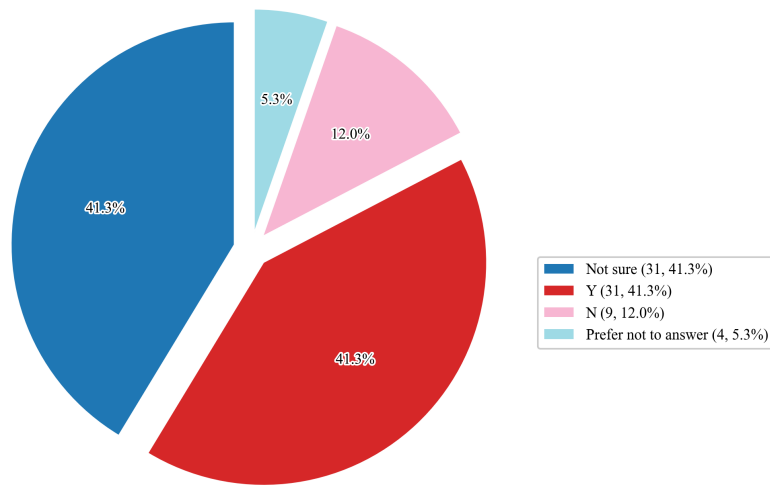


FIGURE 5.34: Responses to “Would you like to help Comet Chasers by using telescopes across the world to take photos of comets?”

not phrased in an understandable way for the students to clearly understand. A large proportion of ‘not sure’ responses are understandable as there is no additional details to the question.

5.3.5.7 Workshop Ranking

How many stars would you give Comet Chasers? (Faint o sêr ti'n rhoi i Cipwyr Comedau)

This question is distinct from the question in section 5.3.5.1 as it asks for a students’ opinion of the workshop rather than their enjoyment of it. Students may

have not personally enjoyed the workshop but could appreciate the workshop as a whole.

TABLE 5.40: Student responses to the question: “How many stars would you give Comet Chasers?”. Responses are ranked from 1 (not good at all) to 5 (fantastic). This question aimed to assess students’ overall opinions of the workshop.

Ranking	Year 4	Year 5	Year 6	PNTA	Total
1	0 (0%)	0 (0%)	2 (7%)	0 (0%)	2 (3%)
2	0 (0%)	0 (0%)	0 (0%)	0 (0%)	0 (0%)
3	1 (6%)	5 (28%)	5 (15%)	0 (0%)	11 (15%)
4	2 (11%)	4 (22%)	8 (24%)	0 (0%)	14 (19%)
5	15 (83%)	6 (33%)	16 (49%)	5 (83%)	42 (56%)
No Response	0 (0%)	3 (17%)	2 (7%)	1 (17%)	6 (8%)
Total	18 (24%)	18 (24%)	33 (44%)	6 (8%)	75 (100%)
Weighted average	4.78	4.07	4.16	5.00	4.36
Median	5	4	5	5	5
Mode	5	5	5	5	5
NPS	94.4%	55.5%	66.0%	83.3%	72.0%

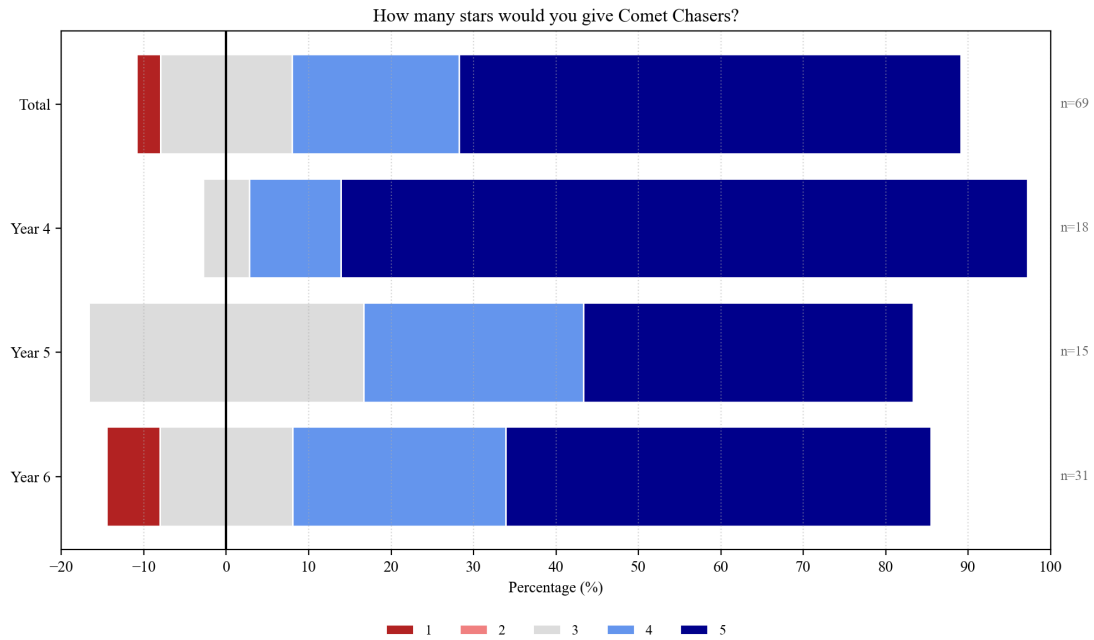


FIGURE 5.35: Diverging stacked bar chart showing the total proportions of responses to the survey question: “How many stars would you give Comet Chasers?”, as well as the distribution broken down by year group. Bars are centred on a neutral midpoint to highlight positive and negative response patterns.

Respondents in Year 4 ranked the workshop the highest, with a weighted average of 4.78 and Net Promoter Score 94.4%, followed by Year 6 (weighted average 4.16, [NPS 66.0%](#)), and finally Year 5 (weighted average 4.07, [NPS 55.5%](#)). All years ranked the workshop very positively, with the mode for each year group being 5. A Kruskal-Wallis test revealed a moderately statistically significant difference between year groups ($H(2) = 7.24$, $p = 0.027$, $\epsilon^2 = 0.09$).

Overall, respondents ranked the workshop highly with a weighted average of 4.36, mode and median of 5, and [NPS](#) of 72.0%, suggesting a fairly strong positive opinion of the workshop as a whole. More respondents overwhelmingly ranked the workshop positively (rank of 4 or 5), than those who ranked it negatively (rank of 1 or 2).

5.3.5.8 Desire for More Comet Chasers Activities

Would you like to do more activities with Comet Chasers?

(Fysa ti'n hoffi gwneud mwy o gweithgareddau gyda Cipwyr Comedau?)

This question was asked to measure the receptiveness of the students to participate in more Comet Chasers' activity, and take a larger part in the project as a whole. This would also highlight the true feelings of the students as if they want to do more with us, then there is no higher praise.

TABLE 5.41: Summary of responses to the question 'Would you like to do more activities with Comet Chasers?'.

Response	Year 4	Year 5	Year 6	PNTA	Total
Yes	13 (72%)	10 (56%)	16 (49%)	4 (67%)	43 (57%)
No	1 (6%)	1 (6%)	5 (15%)	0 (0%)	7 (9%)
Not sure	4 (22%)	5 (28%)	11 (33%)	1 (17%)	21 (28%)
No Response	0 (0%)	2 (11%)	1 (3%)	1 (17%)	4 (5%)
Total	18 (24%)	18 (24%)	33 (44%)	6 (8%)	75 (100%)

Fysa ti'n hoffi gwneud mwy o gweithgareddau gyda Cipwyr Comedau?

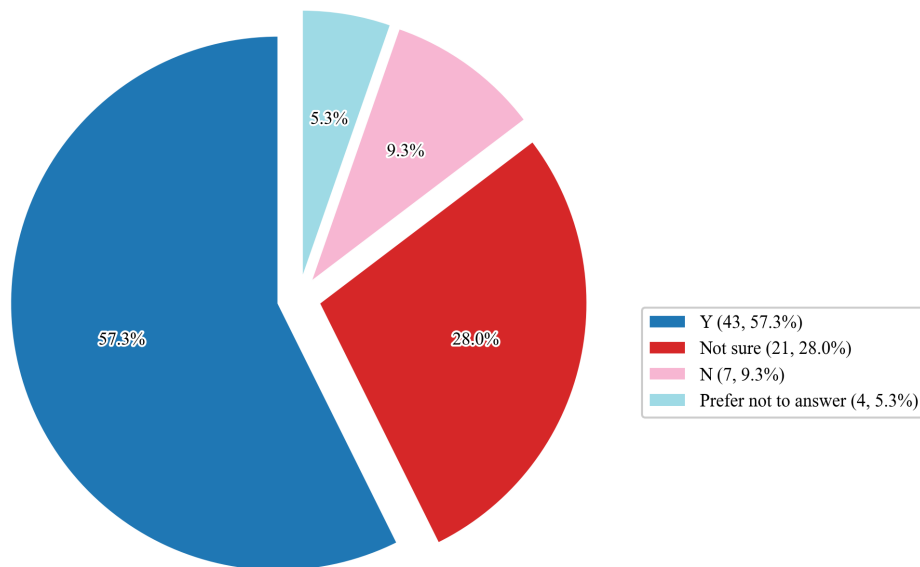


FIGURE 5.36: Responses to "Would you like to do more activities with Comet Chasers?"

On the whole, the majority of students (57%) stated that they would like to do more with Comet Chasers, with only 9% saying they would not like to do more. This is very positive, most students enjoyed the workshop enough to want to further interact with us. A non-trivial proportion of students (28%) said they

were not sure, suggesting mixed feeling. Giving these students the opportunity of trying different activities based on different astronomy topics may help them make their mind up, one way or the other.

Respondents in Years 4 and 5 also had a majority of students state that they would like more activities with Comet Chasers, while 49% of respondents in Year 6 said they would.

It is important to note that respondents from one school mostly responded ‘Yes’ (with only one student selecting ‘Not Sure’), suggesting the teacher may have influenced this response if they themselves would like to be involved - this is believed to be unlikely. All other schools had a variation in the responses by their students.

5.3.6 Summary

75 responses were obtained from 5 different schools. Years 4, 5, and 6 were invited to take part, with 18 respondents from Years 4 and 5 each, and 33 from Year 6 (with the remainder opting not to disclose their school year). All schools, other than School F, consisted of mixed-year classes - either Years 4 and 5, or Years 5 and 6. Respondents from School F were in Year 4. School H provided the most responses (21), with School I providing the least (10).

Most workshops consisted of 3 activities: Rotato, [IR](#) Cameras, and Meteorite Handling. All activities were well enjoyed by the respondents as a whole, with a preference for some.

Students ranked their enjoyment of the Rotato a weighted average of 3.73 out of 5, with a [NPS](#) of 45.7%, suggesting a slight enjoyment of the activity. This activity was most popular with students in Year 4 and 6 ($WA = 3.88$, $NPS = 50.0\%$ and $WA = 3.79$, $NPS = 57.3\%$, respectively), with students in Year 5 ($WA = 3.50$, $NPS = 22.2\%$) enjoying it the least. Some respondents mentioned that they learnt how light behaves and how different colours absorb/reflect the light. Others noted they learnt about graphs and how lightcurves work.

The most enjoyed aspects of the activity were cited as the interactive nature of the experiment, the lightcurve plotting, and objects rotating on the turntable. While many students did say they did not dislike any part of the activity, some mentioned that it was repetitive or confusing, while others mentioned software/equipment issues. Most respondents agreed that this experiment helped them understand how astronomers investigate comets.

As the software was newly developed for these students, they acted as a User Trial to assess any issues that arose during the activity. Most respondents (63%) said that the software was easy to use. Some had issues with the UI of the software, mentioning that text was small or that the graph was difficult to read. Despite some mentioning issues, 40% of students said that they did not dislike the software or find it difficult to use.

Generally, students enjoyed the [IR](#) Cameras activity more than for the Rotato activity. Students gave the [IR](#) Cameras a weighted average of 4.19 out of 5, and [NPS](#) of 64.0%. Respondents in Years 4 ($WA = 4.28$, $NPS = 66.7\%$) and 6 ($WA = 4.16$, $NPS = 65.7\%$) enjoyed the activity more than those in Year 5 ($WA = 3.94$, $NPS = 49.9\%$). Given students in Year 4 enjoyed the activity the most, it could be best suited for younger students, although can be enjoyed by all three year groups surveyed. Learning topics mentioned for this activity consisted of general learning about heat and temperature, how [IR](#) is an ‘invisible colour’, and how humans are warm. Students enjoyed using the cameras to observe their classmates’ body heat and other objects around their classroom. A large proportion of respondents did not have dislikes about the activity, with others mentioning issues with the cameras or issues with sharing that not all had an opportunity to use them.

Again, respondents generally enjoyed the meteorite handling activity with a weighted average of 4.06 and [NPS](#) of 56.0% - lower than for the [IR](#) cameras activity, but higher than the Rotato experiment. Each year group had a roughly equal enjoyment of the activity, with Year 6’s weighted average 3.97, and Years 4 and 5’s weighted average 4.06 - suggesting the activity is best suited for younger

students, but older ones can still enjoy the activity. This activity is enjoyed and appropriate for all year groups surveyed. Students noted they learnt about the age, weight, and magnetism of the meteorites the most. The favourite part of respondents were similar in vein to what they learnt, the age, weight, and magnetism of the samples, but many also said they enjoyed handling the meteorites. Aspects of the activity that respondents disliked involved the cleanliness of the meteorites and their weight, while 30.7% of respondents had positive remarks about the activity mentioning there was nothing they disliked.

Respondents overall view of the workshop was very positive, with the weighted average of their enjoyment being 4.15 and *NPS* of 58.6%. The workshop was most enjoyed by students in Year 6 ($WA = 4.23$, $NPS = 69.6\%$), followed by Year 4 ($WA = 4.12$, $NPS = 55.6\%$), and finally Year 5 ($WA = 3.73$, $NPS = 33.4\%$), suggesting that the workshop is best suited for students either in Year 6 or 4. Meteorite handling was the most popular aspect of the workshop, followed by students saying they enjoyed everything, *IR* cameras, and the Rotato experiment. Many respondents mentioned that there wasn't anything they disliked about the workshop, while a minority expressed general negative sentiments, or specified they disliked the different activities. Respondents had positive suggestions as to how the programme could be improved, with some saying there was nothing to improve, and others requesting more activities or meteorites to handle. Other improvements included adaptations to the way the workshop was delivered by giving more direction, or issues relating to the Rotato software. When asked if they did not understand any aspect of the workshop, 35% mentioned they understood everything, with a small number of students mentioning they did not understand aspects of the rotato, or more generally not understanding the workshop. Many respondents (41.3%) said they would like to help Comet Chasers by using telescopes to image comets.

Overall, students ranked the Comet Chasers workshop 4.36 out of 5 and an *NPS* of 72.0%, suggesting a strong liking of the workshop. The programme was most popular with students in Year 4, followed by Year 6, then Year 5 - rankings from each year group were all over 4 out of 5. Most respondents would also

like to participate in further activities with Comet Chasers, with 57% opting for more. This sentiment was consistent for each year group, although students in Year 5 were more uncertain if they wanted to participate.

On the whole, students most enjoyed the [IR](#) cameras activity ($WA = 4.19$, $NPS = 64.0\%$), followed by Meteorite handling ($WA = 4.06$, $NPS = 56.0\%$), then the Rotato experiment ($WA = 3.73$, $NPS = 45.7\%$). All activities had a positive impression on the students and were generally very positive in what they learnt, enjoyed, and disliked. Year 5 students seemed to not enjoy most activities as much as students in Year 4 and 6 - this could be due to the sample size. Given only 18 responses from students in Year 4 and 5, it is possible these are very enthusiastic Year 4 students, and less so Year 5 students.

Key findings:

- All activities had positive responses by students.
- Students in Year 6 enjoyed the Rotato activity the most, with students in Year 5 enjoyed it the least.
- [IR](#) cameras activity was more popular amongst students than the Rotato experiment, with students in Year 4 enjoying it the most.
- All year groups of students enjoyed meteorite handling activity roughly equally.
- Overall, students enjoyed the workshop, with students in Year 6 enjoying it the most.

5.4 Reflections and Conclusions

5.4.1 Attitudes towards Science and Astronomy

While art is the most popular subject listed by students, a job in [STEM](#) was most popular for their future. Arts and humanities subjects were more popular than [STEM](#) subjects. Interestingly, art was the most popular subject for those who selected jobs in [STEM](#), art, healthcare, and hospitality. Maths was the most popular subject for those who opted for jobs in the police and education.

Enjoyment of science lessons were ranked 3.7 out of 5, with students' enjoyment decreasing as they age. Enjoyment of learning about space was more positive than for science lessons, with a ranking of 3.9 out of 5. As students age, their attitudes towards space shift towards neutrality, implying that the excitement may wane by age 11. Students would like to learn more about space in science lessons, although this is not an overwhelming majority.

Conducting workshops with students in primary school would be a beneficial way to introduce science and to nurture interest as early as possible. This could help mitigate the reduced interest that occur as schools age.

Most students can correctly identify images of stars, galaxies, and planets, while struggling to differentiate meteors and comets. This gives validity in trying to teach students about comets, asteroids, and meteors, it is clearly a lesser known side of astronomy. Students who enjoy science and space were far more likely to identify these objects correctly.

This survey highlighted the importance of involving art and creative activities into science workshops. It would be a beneficial way to introduce students who are not very interested in science.

5.4.2 Workshop Feedback

Overall, feedback towards the workshop is very positive, gaining an enjoyment rating of 4.2 out of 5, and given 4.4 stars out of 5. Most students had positive sentiments towards the workshop, with most not citing any problems or dislikes. The workshop was most popular with students in Year 4, followed by Year 6, then Year 5. When queried about their favourite aspect of the workshop, the most popular was meteorite handling, ‘everything’, IR cameras, and the Rotato experiment. No significant statistical difference was observed between the school years’s enjoyment of the different activities, suggesting the activities on the whole have a broad appeal for students of different ages.

IR cameras activity gained a rank of 4.2 out of 5, with this activity most popular with students in Year 4. This being the activity ranked the highest out of the three conducted. Some noted that they had some issues with the cameras, such as problems functioning the cameras. Despite this, most responses did not have issues, and provided positive sentiments about the activity.

The meteorite handling activity was ranked the second most popular with respect to the respondents’ enjoyment, with a rank of 4.1 out of 5. Students in Year 4 and 5 ranked their enjoyment 4.1, while students in Year 6 ranked 4.0. They mostly marvelled at the age of the meteorite samples, with some mentioning they would have liked to have more samples to hold and experiment with.

Enjoyment of the Rotato activity was ranked lowest, 3.7 out of 5, most popular with students in years 4 and 6. The favourite aspects of the activity were the interactivity and freedom students had to experiment with it. Some noted that they found the activity repetitive or boring, suggesting more structure may be needed to keep things interesting and to continue the work to flow, although most had positive sentiments about the activity. Most students mentioned that the experiment helped them understand how astronomers can deduce different features of astronomical objects.

All activities were positively viewed, although students in Year 5 generally ranked their enjoyment lower than those for Years 4 or 6. Each activity conducted in these workshops have their own positives and could have huge impact on students' interest in science and astronomy.

Both meteorite handling and IR cameras activities are very good ways to introduce astronomy to students, and as to increase interest towards those subjects. Students find the activities enjoyable and appear to learn about important astronomical concepts in an unstructured and very explorative way.

The Rotato experiment does not function at its best in short workshops such as these. There are too many distractions in this environment for students to fully be able to focus on the activity. When teachers or myself would sit and interact with the students as they experimented, more progress would be made, and it made students think critically about the activity. Teachers structuring the activity more like a 'normal' lesson would benefit students' learning, mainly as a way to keep the students continuing their learning. Additionally, giving students more time to conduct the activity (more than the ~30 mins allotted for these workshops) could allow more detailed experimentation. This activity should not be the first activity conducted as part of a series of workshops as it would not capture the interest of the students as much as IR cameras or meteorite handling, but it has more in-depth learning points.

Having more than one presenter is crucial for future workshops. It is not beneficial for either presenter nor the students for a single person to deliver the workshop. It is difficult to address issues that occur during activities, and sitting with students doing activities aids their understanding and enthusiasm towards the activity.

5.4.3 Comet Chasers' Future

Comet Chasers should focus on longer-term interventions, to maximise effectiveness and ensure that the activities can have the greatest impact possible. Focussing on an activity each session would allow more intense experimentation, allowing students to investigate the concepts and ask themselves questions about the task. Targeting students at Years 4 and 5 could help maximise their interest in science lessons, with enough time before they begin secondary school to spark their interest. Beginning the series of workshops with meteorite handling would be an ideal way to introduce students to learning about astronomy, as it is a tangible way to connect students with objects and concepts which seem impossibly far away from students' normal lives.

For the programme to be conducted by teachers, without external interventions, a coherent and complete package should be created. This should include detailed teacher guides and student worksheets, accompanied with videos explaining clearly how the activities should be set up.

Part II

Cometary Science: Using Comet Chasers' data in astronomical research

Chapter 6

Photometric Pipeline

6.1 Pipeline Requirements

Thousands of images are available in the LCO archive of [29P/SW1](#) over the last 10+ years, processing and conducting photometry on each image using software like Astrometrica (Raab [n.d.](#)) would be extremely laborious. The main aim of this photometric pipeline was to speed up the processing and analysis of minor-bodies, specifically comets. Despite needing some user input to process these images, it speeds up the analysis immensely.

Additionally, the pipeline needed to be universal and complete for minor-bodies with the final aim of having school students utilise the tools developed to analyse their own images. Allowing students to analyse their images using professional standard software will cement the students firmly in the scientific process.

Key requirements:

1. Batch processing images.
2. Speed up individual processing times.
3. Minimal user input.
4. Universal adaptability (not exclusive to one object).

5. Reliable and repeatable results.

6.2 Development

The photometric pipeline was written in Python. Numerous iterations of this pipeline have been written and reworked.

6.2.1 Image Selection, Stacking and Background Reduction

The first part of the photometric pipeline is image selection. The user is prompted by a window to select the .fits or .fz files they wish to process. To ensure images have not been previously processed, there is a check to see if the images selected by the user correspond to any files already processed and saved in the output file.

Stacking images primarily works for [LCO](#) images due to their naming convention, though can be adapted manually to accommodate non- [LCO](#) images. Images selected by the user are grouped into lists for each observing run, dependent on the observatory location, telescope used, date observed, and number of images taken by the telescope on that day. Each observing run will consist of images from the same location, telescope, date, and with consecutive image numbers. If the observing run consists of more than 4 images, then the group is split up as equally as possible.

Due to the [LCO](#) observing runs occurring fairly quickly, the telescope (or comet) does not move much between frames. This simplifies the stacking process, as the images can simply be summed together.

[Source Extraction and Photometry Python Package \(SEP\)](#) (Barbary 2016) has a function *Background*, which calculates a variable background and noise array, to be subtracted from the image array.

6.2.2 Astrometric Calibration, Target Alignment, and Star Detection

Despite [LCO](#) images being processed via the BANZAI pipeline (McCully et al. [2018](#)), occasionally, errors occurred citing that reference stars were not matching with catalogues for the supplied central position of the image. A simple fix for this was to ensure the central position of the image is accurate with respect to the stars seen in the image. This was done by using the website [astrometry.net](#) (Lang et al. [2010](#)) via their web API to obtain the image position. While a necessary process, this is the step that takes the longest in the pipeline and to save time while testing, the data obtained from [astrometry.net](#) is saved for future use. This was useful when testing the pipeline using the same series of images, as processing would occur far quicker as it did not have to query again using the API.

Additional data is needed for analysis, and is obtained from [Jet Propulsion Laboratory \(JPL\)](#)'s Horizons system (Giorgini [2025](#)). Data includes: estimated target RA and declination, [heliocentric](#) distance, [geocentric](#) distance, phase angle, and solar position angle. This is obtained using the package 'astroquery' (Ginsburg et al. [2019](#)). The data obtained is used as the initial guess as to the location of the target before the position can be refined with respect to the image, and to calculate the reduced magnitude.

Using the target's Horizons position (here-on called initial position), the [Point Spread Function \(PSF\)](#) of the target is calculated. Both the x and y axis [PSF](#) are calculated to better find the nuclear position. An axis's [PSF](#) is calculated by plotting the intensity of a pixel versus the pixel position within the row/column which passes through the initial position. A Gaussian fit is fitted to the data using the 'curve_fit' function from the SciPy package (Virtanen et al. [2020](#)). The pixel position of the peak of the Gaussian is used as the realigned nuclear position.

For comets, the PSF is not a perfect Gaussian curve as the object is not a point source due to the coma. The asymmetry is more noticeable after an outburst as material from within the nucleus is ejected in (primarily) one direction. Despite this, a symmetrical Gaussian fit is sufficient to find the maximum position for both PSF axes.

Often, the realigned position is accurate to by-eye estimations of the nuclear position, unfortunately, this is not always the case. Issues in the realignment can be caused by the initial position being too far from the actual nuclear position, or the coma appearing so bright that it affects the fit of the Gaussian. After trying to remedy this, I realised the simplest step was to manually check and realign the nuclear position. A ‘tkinter’ (Lundh 1999) window opens showing the area around the realigned position with the initial and realigned positions labelled. The user can either use the realigned position or select the position themselves. This ensures that the nuclear position is correct. While this does slow down the processing speed of each image, it is worthwhile as before introducing this feature, numerous data points were far from correct due to incorrect alignment.

Following manual alignment, the PSF is again calculated, see fig. 6.1 for an example. Notice that the data does not fully fit the symmetrical Gaussian fit.

Following identifying the target, the stars in the image also need identification. The package SEP (Barbary 2016; Bertin and Arnouts 1996) was used to find the sources in the image. The flux of these sources are measured using an aperture size defined by the user. These sources are matched with stars in the PanSTARRS 1 catalogue via the package Calviacat (Kelley and Lister 2024). Sources without corresponding reference stars in the catalogue are excluded as they cannot be used to calculate the magnitude of the target. Additionally, any catalogue star which does not have a recorded magnitude in the same filter as the image being processed is also excluded.

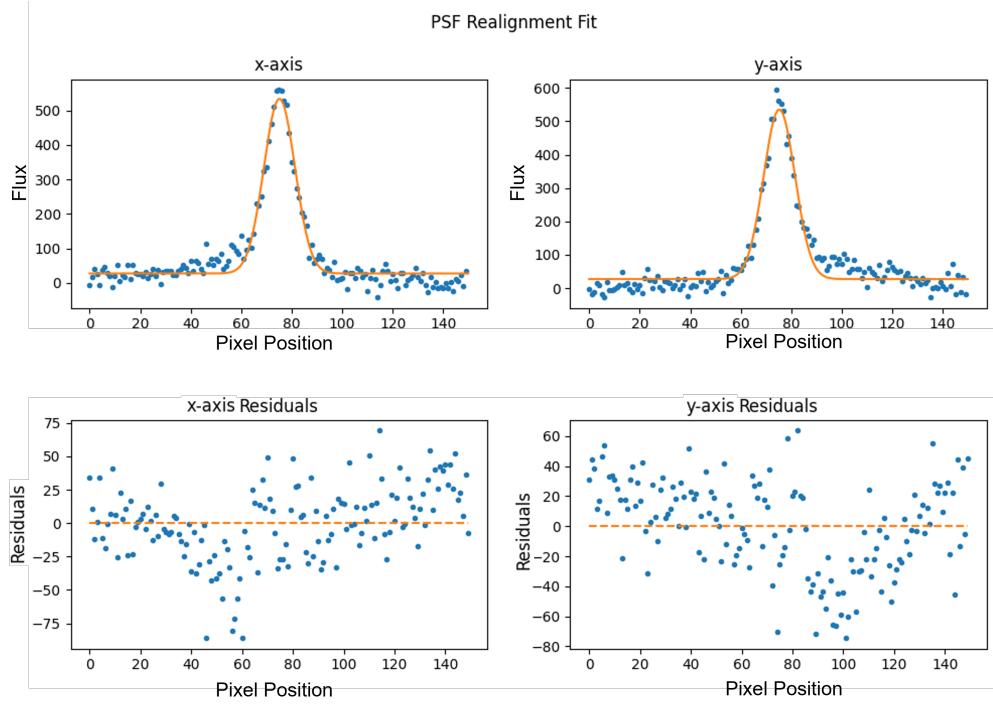


FIGURE 6.1: [Point Spread Function](#) and their respective residuals for both x and y axis after realignment is completed.

6.2.3 Basic Photometry

For a given source (either the target or reference star), the flux is measured using apertures defined by the package [SEP](#) (Barbary 2016). A consistent aperture size is used for all sources.

Using the star and target fluxes measured and the star magnitudes queried from catalogues, the magnitude of the target can be calculated. Each reference star is used to calculate the apparent magnitude of the target using the following equation.

$$m_{target} = m_* - 2.5 \log_{10} \left(\frac{f_{target}}{f_*} \right) \quad (6.1)$$

where m is the apparent magnitude and f is the measured flux. The output of using this equation is an array of the magnitude of the object with respect to each reference star individually. The error for each calculated magnitude is done via quadrature:

$$\sigma_{m_{target}} = \sigma_{m_*}^2 + \left(\frac{-2.5}{f_{target} \ln(10)} \right)^2 \sigma_{f_{target}}^2 + \left(\frac{2.5}{f_* \ln(10)} \right)^2 \sigma_{f_*}^2 \quad (6.2)$$

Simplified, this can be expressed as,

$$\sigma_{m_{target}} = \sigma_{m_*}^2 + \left(\frac{2.5}{\ln(10)} \right)^2 \left(\left(\frac{\sigma_{f_{target}}}{f_{target}} \right)^2 + \left(\frac{\sigma_{f_*}}{f_*} \right)^2 \right) \quad (6.3)$$

where σ is the associated error. This method of error analysis was based on that described by Castro et al. (2020).

A weighted average is calculated using,

$$\Delta X^2 = \frac{1}{\sum_i \sigma_i^{-2}} \quad (6.4)$$

$$X = \Delta X^2 \sum_i \frac{x_i}{\sigma_i^2} \quad (6.5)$$

where X is the weighted average with error ΔX , x_i is an entry in the list to be averaged with corresponding error σ_i .

Using a weighted average is very important as it accounts for the errors associated with magnitude measurements. Due to the software automating source detection and star matching with published catalogues, many stars are used as reference stars, this value ranges from tens to thousands depending on the image. The sheer number of reference stars allows us to be selective with the stars used, stars with a larger associated error will have less impact on the final average, leading to a more reliable value.

6.2.4 Signal-to-Noise Ratio

The **SNR** is a measure, generally, of the 'goodness' of an observation. A high **SNR** usually means the image is of higher quality as the signal (i.e. the sources in the image) is much greater than the noise (i.e. the background). While this is not always the case, the **SNR** is a good indication of the quality of the image post-processing.

Unfortunately, this ratio is not as simple as signal divided by noise. It can be calculated using,

$$\frac{S}{N} = \frac{N}{\sqrt{N + n_{pix}(N_S + N_D + N_R^2)}} \quad (6.6)$$

where N is signal, i.e. the flux of the target, n_{pix} is number of pixels used to calculate the flux, N_S is number of photons per pixel for the background, N_D is dark current in electrons per pixel, and N_R is read noise in elections per pixel Howell 2006, Section 4.4.

Equation 6.6 can be simplified if the source flux dominates the equation,

$$\frac{S}{N} = \sqrt{N} \quad (6.7)$$

where, again, N is signal Howell 2006, Section 4.4. As comets are faint sources (other than during an outburst), equation 6.6 is used. If any parameter, like dark current or read noise, is not available for a given observation, the simplified equation 6.7 is used.

6.2.5 Multi-Aperture Photometry

Multiple measurements were made using apertures of incrementally larger aperture diameters. Radii start at 1" in intervals of 1" to 25". Calculating the magnitude for varying aperture sizes gives an indication of how the coma brightness varies at differing distances from the nucleus.

Using these measurements allow estimations of the nuclear diameter, radial profile, and surface brightness variations as radial distance increases.

While this functions well, the output data is not as concise and easy to manipulate, therefore this is a significant part which will require changes in future iterations, more in sect. 6.3.

6.3 Future Revisions

While the pipeline functions well and effectively, a lot was learnt while programming for it to be written more effectively to maximise its efficiency and quality.

Better ways to store the data would be enormously useful. Currently, different aperture size measurements are stored in a separate file to the main data output containing observation details. A better method should be used to make accessing the data far simpler. Using a more user-friendly interface to process the images would also aid in simplicity of using the pipeline. This could include options to select which photometric processes were conducted, plus parameters. For example, the aperture sizes used could be defined initially, rather than hard coded into the pipeline, including start, end, and interval size for aperture diameters.

More reliable results could be measured if the uncertainties package (Lebigot [2017](#)) was used, making error analysis far simpler. Pairing this with a more sophisticated stacking function would further increase the reliability of the measurements. Stacking more images from a night's observing, ensuring that the target is aligned, would further increase the [SNR](#).

Making the pipeline more versatile for different telescope setups would allow easier use for images obtained from sites not part of the [LCO](#) network. This could include using the darks, flats, and bias frames to calibrate the lights. Additionally, having the option to query different star catalogues to access star magnitudes in different filters would also add to the potential versatility.

Finally, implementing this pipeline online and available for students taking part in the Comet Chasers' programme would further involve the students as they become active parts of the analysis of images, not just requesting the images.

Chapter 7

29P/Schwassmann-Wachmann 1: Long-Term Analysis

7.1 Orbital Changes

Since [29P/SW1](#)'s earliest precovery in 1902, its orbit has changed greatly. As Centaurs are transitional objects (Sarid et al. [2019](#)), this is unsurprising.

Numerous orbital parameters, derived since its discovery, are shown in table [7.1](#), highlighting the significant changes in orbital period and [eccentricity](#) over <100 years. As [29P/SW1](#)'s orbit is just beyond that of Jupiter's, its orbit will occasionally be perturbed by Jupiter. Close approaches since its discovery and next approach were calculated by (Giorgini and Yeomans [1999](#)) and are displayed in table [7.2](#).

Most of the orbit calculations at different epochs available on [JPL](#) Horizons did not contain all the parameters displayed in table [7.1](#) - usually only [perihelion](#) distance and [eccentricity](#). It was possible to calculate the other parameters using equations [7.1](#), [7.2](#), and [7.3](#).

$$q = a(1 - e) \tag{7.1}$$

TABLE 7.1: Orbital parameters for calculated orbits at various epochs since 29P/SW1’s discovery. Parameters are calculated based on position of objects from observations. Data obtained from Giorgini and Yeomans (1999) and MPC Database Search (2025). Horizontal lines between rows represent time in which the object has a close approach with Jupiter, likely causing perturbations to its orbit.

Epoch	T (yrs)	e (°)	a (AU)	q (AU)	Q (AU)	i (°)	Source
2025-11-21	14.91	0.043	6.06	5.80	6.32	9.36	MPC
2022-10-14	14.87	0.045	6.05	5.78	6.32	9.36	JPL
2007-03-09	14.65	0.044	5.99	5.72	6.25	9.39	JPL
1974-02-02	15.03	0.105	6.09	5.45	6.73	9.75	JPL
1957-05-02	16.10	0.131	6.38	5.54	7.21	9.49	SAO
1941-05-06	16.14	0.135	6.39	5.52	7.25	9.52	SAO
1925-05-10	16.44	0.153	6.47	5.47	7.46	9.44	SAO
1908-10-26	16.44	0.150	6.46	5.50	7.43	9.42	SAO

$$Q = a(1 + e) \tag{7.2}$$

$$T = 2\pi\sqrt{\frac{a^3}{GM_\odot}} \tag{7.3}$$

TABLE 7.2: Closest approaches of Centaur 29P/SW1 to Jupiter since the object’s discovery. A future close approach is also included.

Date	r_J (AU)
1930-07-13	1.95
1974-05-21	1.00
2037-10-11	0.90

Since discovery, two close approaches to Jupiter have occurred, and both events deviated its orbit. Another close approach will occur in 2037, nearer than either of the previous known interactions, and potentially perturbing its orbit to a greater extent.

Following the 1930 close approach, 29P/SW1’s orbit was perturbed, leading to a more circular orbit (reduced [eccentricity](#)), shorter orbital period, and narrower [heliocentric](#) orbital range. The interaction in 1974 occurs three months

after the epoch of the 1974 orbital calculation, but uses positional data from observations from 1902 to 1997, therefore spanning periods within which both close approaches with Jupiter occur, suggesting why these parameters deviate from previous and subsequent epochs.

Calculations of epochs in 2007, 2022, and 2025 all use data following the most recent close approach in 1974, portraying an accurate representation of how the interaction affected the orbit. Orbital calculations in the 21st century suggest that the object’s orbit is slowly becoming more circular, with an increasing orbital period and hence migrating further from the Sun.

TABLE 7.3: Perihelion dates and distances for 29P/SW1 since 1941. The next perihelion data is included. Data credit: (Giorgini and Yeomans 1999)

Date	r_H (AU)
1941-04-21	5.52
1957-05-12	5.54
1974-02-15	5.45
1989-10-26	5.77
2004-06-26	5.72
2019-04-16	5.77
2035-02-18	5.71

Since its discovery, 29P/SW1 has reached perihelion 6 times, and the dates and heliocentric distances are shown in table 7.3. Dates and distances obtained from (Giorgini and Yeomans 1999).

7.1.1 Temperature Variations

Using 29P/SW1’s current perihelion and aphelion distances, it is possible to estimate the temperature of the body at these points. Given the eccentricity is very low, temperature difference would not be extreme, but will give an indication of how its orbit may affect the local environment within the Centaur nucleus, or if its orbit could influence its activity.

Swihart (1992) gives an expression to calculate the temperature of an object orbiting the Sun at distance r .

$$T = \sqrt[4]{\frac{L_{\odot}}{4\pi\sigma} \frac{A_{abs}}{A_{rad}} \frac{1-a}{\varepsilon r^2}} \quad (7.4)$$

where $L_{\odot}$ is solar luminosity, σ is Stefan–Boltzmann constant, A_{abs} is the area which radiation is absorbed by an object, A_{rad} is the area which radiation is emitted/reflected by an object, a is the albedo, ε is emissivity of the object, and r is the [heliocentric](#) distance in km.

Bauer et al. (2013) measured the albedo of 29P/SW1 to be $a = 0.033 \pm 0.015$. The emissivity is affected by the object’s coma, we use $\varepsilon = 0.9 \pm 0.1$ for 29P/SW1, similar to values used for 2I/Borisov (Jewitt et al. 2020).

$\frac{A_{abs}}{A_{rad}}$ is the proportion in which radiation is absorbed to reflected, dependent on the rotational period of the object, defined by Swihart (1992) as $\frac{A_{abs}}{A_{rad}} = 1$ for the subsolar point on a slowly rotating body, $\frac{A_{abs}}{A_{rad}} = \frac{1}{2}$ for the average temperature for a slow rotating body, and $\frac{A_{abs}}{A_{rad}} = \frac{1}{4}$ for the average temperature for a fast rotating body. ‘Slow’ and ‘fast’ rotators are fairly arbitrary terms, and are not quantified numerically by Swihart (1992), but are approximates based on night-side cooling. Calculated temperatures using these parameters are displayed in table 7.4.

TABLE 7.4: Temperature estimates of 29P/SW1 at its current [perihelion](#) and [aphelion](#) distances based on approximate rotational speeds. Values were derived from equation 7.4 and have been rounded to the nearest 5 K

due to the approximate nature of the $\frac{A_{abs}}{A_{rad}}$ parameter.			
Rotation Assumption	$\frac{A_{abs}}{A_{rad}}$	$T_{perihelion}$ (K)	$T_{aphelion}$ (K)
Sub-solar (Slow Rotator)	1	170 ± 5 ($\sim -100^{\circ}\text{C}$)	160 ± 5 ($\sim -115^{\circ}\text{C}$)
Average Slow Rotator	$\frac{1}{2}$	140 ± 5 ($\sim -135^{\circ}\text{C}$)	135 ± 5 ($\sim -140^{\circ}\text{C}$)
Average Fast Rotator	$\frac{1}{4}$	120 ± 5 ($\sim -150^{\circ}\text{C}$)	115 ± 5 ($\sim -160^{\circ}\text{C}$)

For a slowly rotating object, the difference between the [sub-solar point](#) and the average temperature for the object at [perihelion](#) is $\sim 25\text{K}$. The [sub-solar point heliocentric](#) temperature at [perihelion](#) and [aphelion](#) varies from $170 \pm 5\text{ K}$ to $160 \pm 5\text{ K}$, respectively - a $\sim 10\text{ K}$ change. Similar variations in average temperatures occur for a slow and fast rotator between temperatures at [perihelion](#) and [aphelion](#) ($\sim 5\text{ K}$).

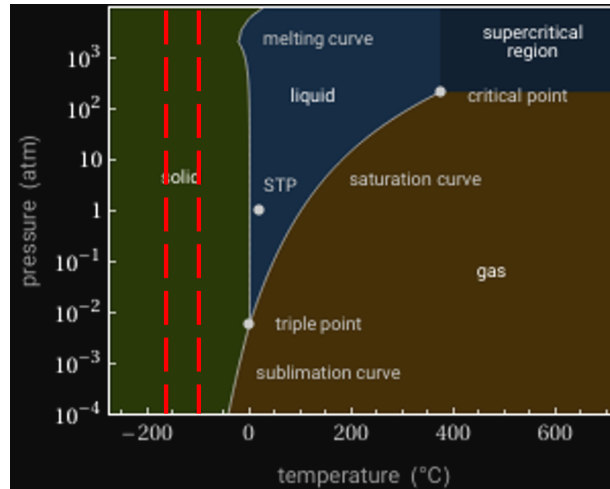
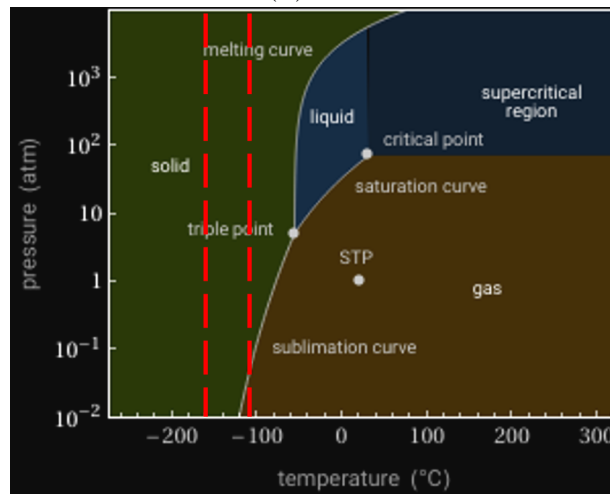
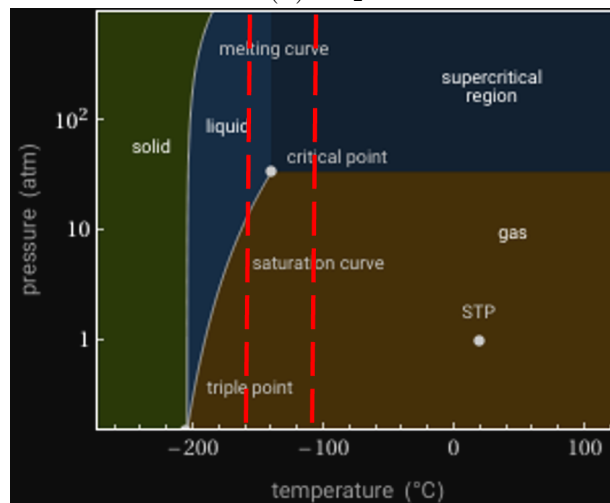
Figure 7.1 shows the phase diagrams of H_2O , CO_2 , and CO - all common [volatiles](#) within cometary nuclei. Maximum and minimum temperatures from tab. 7.4 are shown as vertical dashed red lines to display the potential temperature range of 29P/SW1.

At low pressures, the transition for a slow rotator from the average to sub-solar temperature could cross the [sublimation](#) curve for CO_2 . For H_2O and CO , the temperature range lies firmly within a single state - solid and gas respectively. This suggests that if activity is driven by [sublimation](#) of ices within the Centaur's nucleus, then it must be predominantly driven by [sublimation](#) CO_2 sublimation.

7.2 Historical Data

Historical observations of 29P/SW1 were retrieved from numerous sources - tab. 7.5 summarises the number of data points for each source, which cover a range of different aperture size measurements and filters. Data from published articles, [ATels](#), [MPC](#) observation submissions, amateur campaigns, and LCO images were used to compile this extensive dataset of **142,650** measurements.

An almost 98-year (apparent magnitude) lightcurve was produced using this data, separated into 20 year subplots for ease of viewing - see figure 7.2. [Perihelion](#) dates and near encounters with Jupiter are displayed as vertical lines. The cadence of observations greatly increase from 2003 onwards, giving a highly detailed lightcurve in multiple filters over the past ~ 20 years.

(A) H₂O(B) CO₂

(C) CO

FIGURE 7.1: Phase diagrams for H₂O, CO₂, and CO. Plots produced by Wolfram-Alpha using data from Huber et al. (2018). These plots show the threshold for changing phases at different pressures and temperatures. Vertical dashed red lines represent the maximum and minimum temperatures shown in table 7.4.

TABLE 7.5: Summary of number of data points supplied by each literature sources used to build the ~ 100 year lightcurve of [29P/SW1](#).

Source	Date Range	n
Biesbroeck (1927)	Nov 1927	1
Richter (1941)	Nov 1927 - Jun 1939	140
Whipple (1980)	Nov 1927 - Feb 1977	463
Biesbroeck (1931)	Feb 1931	2
MPC Database Search (2025)	Feb 1932 - Jun 2025	44061
Richter (1952)	May 1939 - May 1950	207
Mayall (1941)	Sep 1941	1
Biesbroeck (1943)	Jan 1943	2
Jeffers (1956)	May - Jul 1955	4
Roemer (1958)	Jul - Dec 1957	8
Walker (1959)	Dec 1958	2
Marsden (1976)	Oct 1976	7
Kiselev and Chernova (1979)	Dec 1976 - Feb 1977	13
Jewitt (1990)	Jun 1987 - Dec 1988	89
Meech et al. (1993)	Aug 1987	116
Moreno (2009)	Jul 2004	35
Bockelée-Morvan et al. (2022)	Dec 2007 - Nov 2021	655
Trigo-Rodríguez et al. (2010)	Jan 2008 - Jun 2010	313
Kidger (2010a)	Apr 2010	5
Kidger (2010b)	Apr 2010	3
Hosek et al. (2013)	May 2011 - Jul 2012	26
Ivanova et al. (2016)	Feb 2012	12
Shubina et al. (2023)	Jan 2012 - Oct 2019	59
Wierzchos and Womack (2020)	Feb 2016 - Jan 2019	129
Miles (2024b)	Jul 2016 - Jul 2025	20602
Picazzio et al. (2019)	Aug 2016	16
Kokhirova et al. (2020)	Jul - Aug 2017	18
Voitko et al. (2022)	Aug - Oct 2018	18
Lin (2023)	Sep 2018 - Dec 2021	214
Bodewits et al. (2019)	Aug - Sep 2019	13
Clements and Fernandez (2021)	Sep 2019 - Jan 2020	155
Donaldson and Scholz (2020)	Dec 2019 - Feb 2020	9
Ye et al. (2019a)	Jun 2019	2
Ye et al. (2019b)	Aug 2019	4
Ye et al. (2019c)	Oct 2019	11
Kochergin et al. (2021)	Feb 2021	28
Kelley et al. (2021a)	Mar - Apr 2021	16
Sharma et al. (2021a)	Sep 2021	5
Sharma et al. (2021b)	Oct 2021	12
Kelley et al. (2021c)	Nov 2021	9
Betzler (2023b)	Dec 2022	3

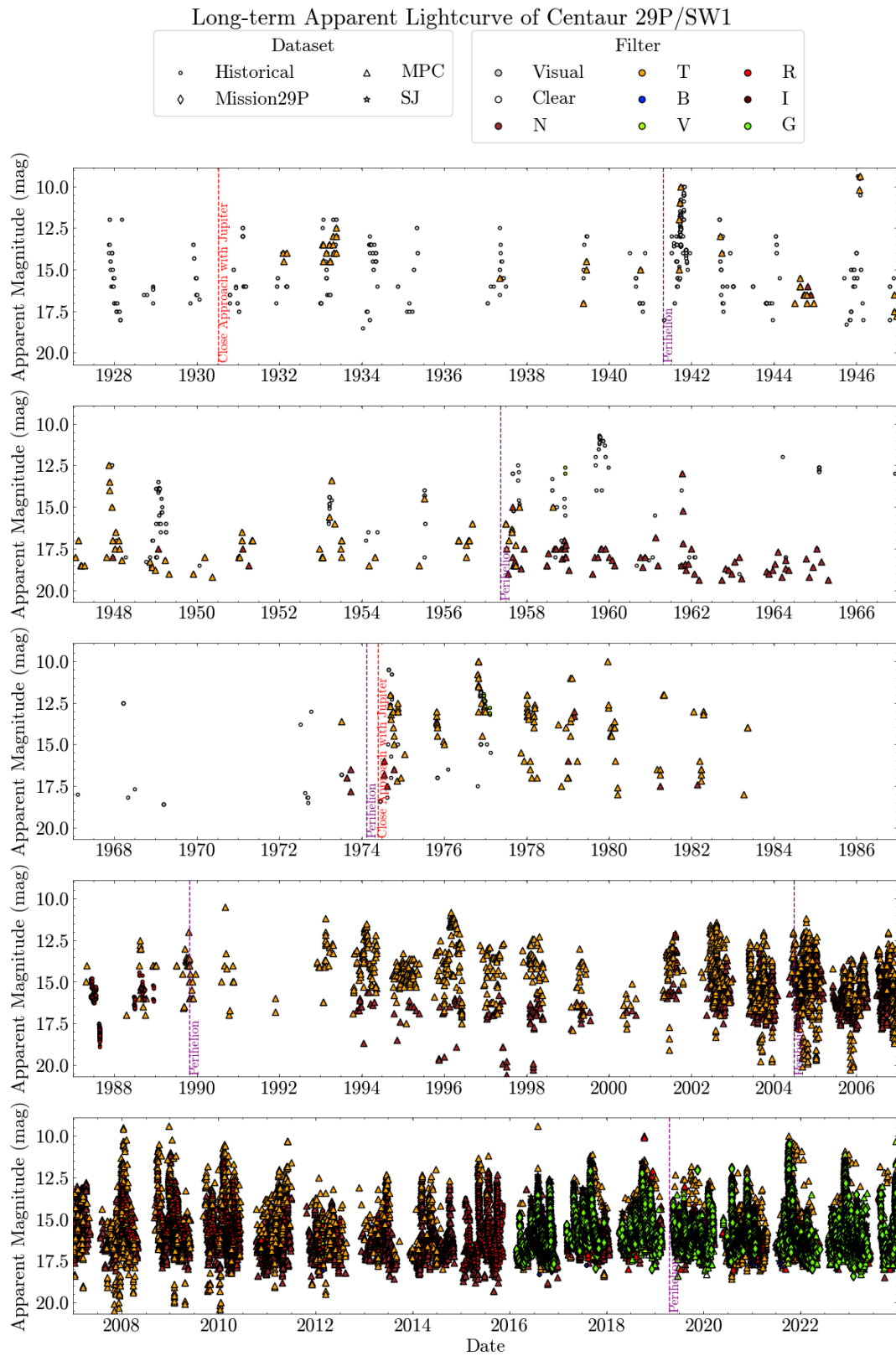


FIGURE 7.2: Long-term apparent magnitude lightcurve of Centaur 29P/SW1, from its discovery in 1927 to present day. Each subplot represents 20 years of data. Data was obtained from published articles, MPC observation submissions, and BAA's Mission 29P.

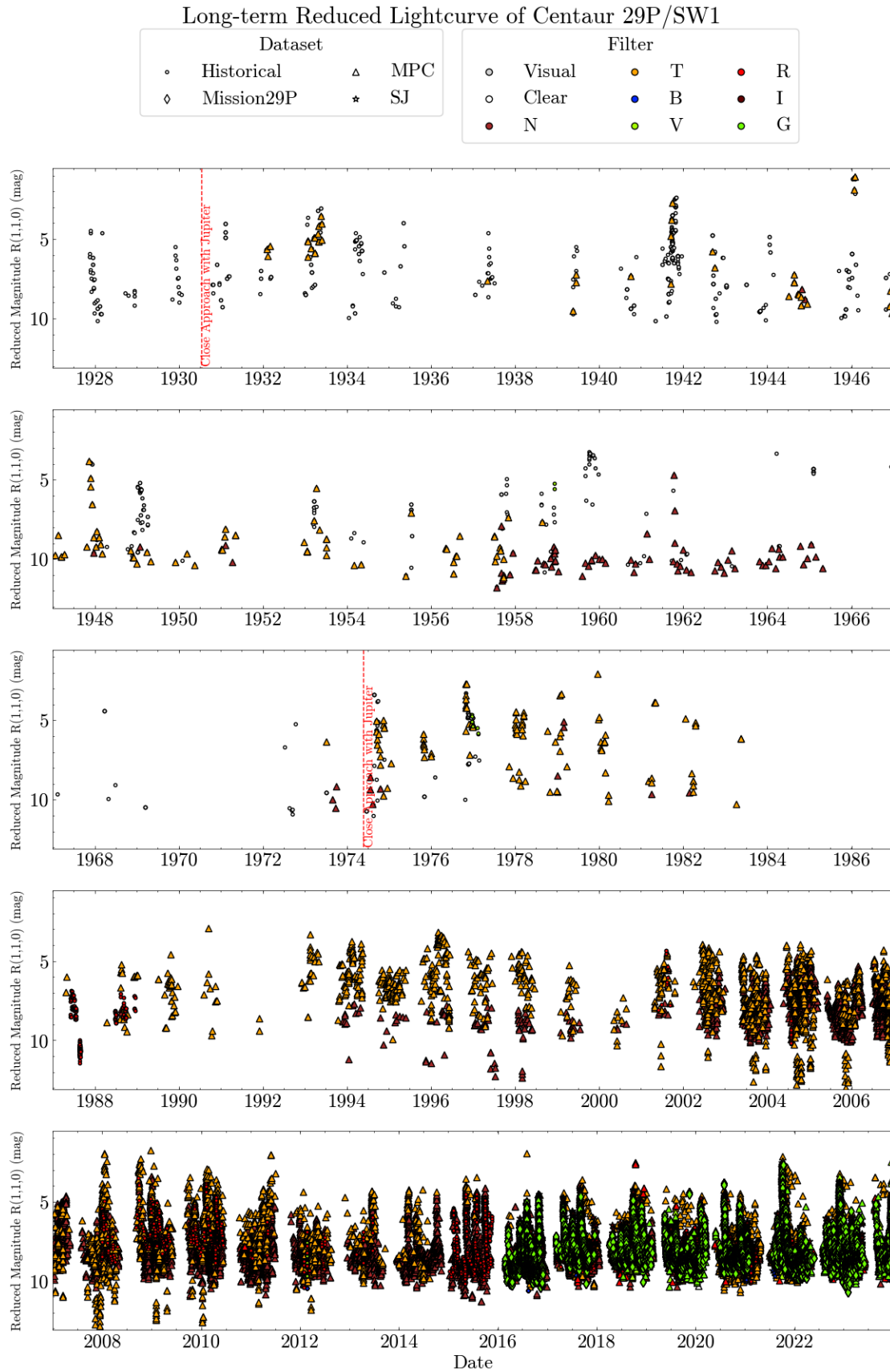


FIGURE 7.3: Long-term reduced magnitude lightcurve of Centaur 29P/SW1, from its discovery in 1927 to present day.

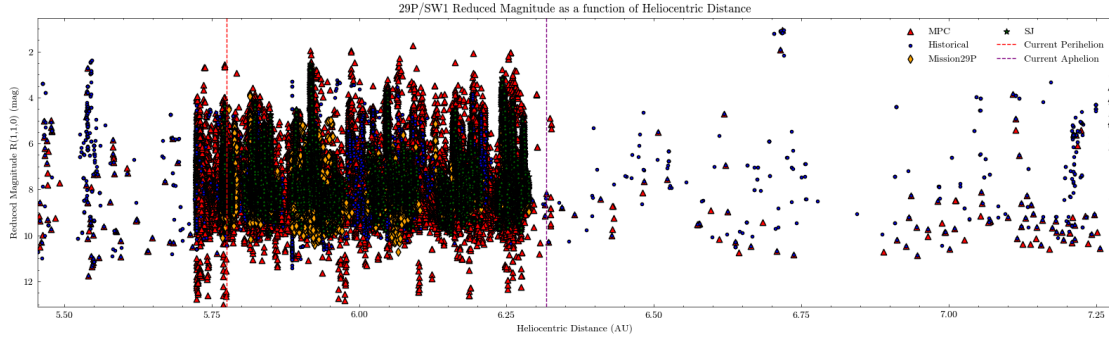


FIGURE 7.4: Reduced magnitude against [heliocentric](#) distance. Dashed vertical lines represent the [perihelion](#) and [aphelion](#) for the most recent orbit calculations in 2022 by Giorgini (2025).

There appear to be far more outbursts occurring within the Centaur’s current orbit rather than at older, less circular orbits. This is expected to be due to sampling bias, as the observing cadence in the last ~ 10 years has greatly increased, leading to a natural increase in the number of outbursts detected. Outbursts with peak magnitudes $\sim 2 - 4$ mag do occur in the older datasets, showing that large outbursts are not a new occurrence for this Centaur. Maximum reduced magnitude appears to remain fairly consistent at $R(1, 1, 0) \sim 10$ mag.

This historical dataset contains 6 complete orbits worth of data, with [perihelion](#) dates listed in table 7.3. Plotting reduced magnitude against the [heliocentric](#) distance shows whether the Centaur’s activity varies at different distances from the Sun, see figure 7.4.

This plot clearly shows how dynamically unstable [29P/SW1](#)’s orbit is, as over the almost 100 years since its discovery, its orbit has varied considerably, with its [perihelion](#) distance increasing from 5.45 AU to 5.77 AU, and [aphelion](#) distance reducing from 7.28 AU to 6.32 AU.

The influence of the joviocentric distance of the Centaur is displayed in figure 7.5. Reduced magnitude is plotted against distance from Jupiter to assess if nearer approaches to Jupiter could affect the frequency and intensity of outbursts.

Due to the high cadence of observations of [29P/SW1](#) in the last 15+ years, it is clear that activity remains frequent and intense at joviocentric distances greater

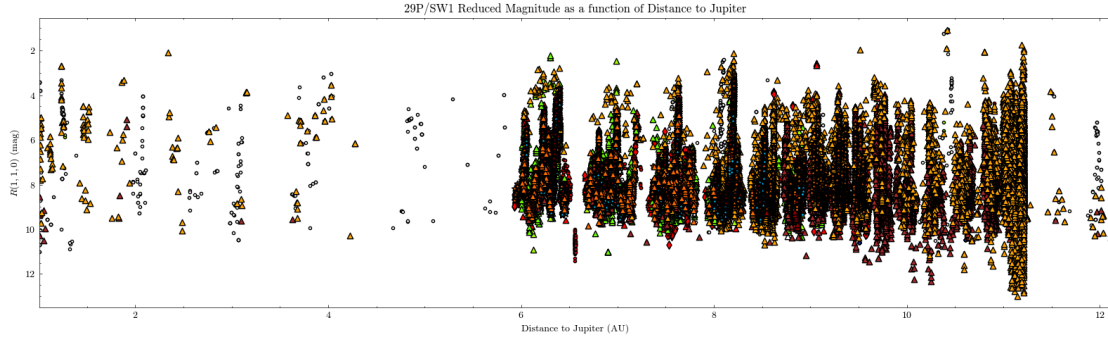


FIGURE 7.5: Reduced magnitude variation with respect to jovicentric distance.

than 6 AU. While close approaches with Jupiter have a major effect on the orbit of the object, they do not seem to affect the intensity nor frequency of outbursts.

7.3 Long-Term Summary

[29P/SW1](#) has always exhibited intense and regular outbursts. Up until the 21st century, it was not clear how frequent these outbursts occurred due to the infrequent nature of observations.

Since its discovery almost a century ago, its orbit has become more circular following close approaches with Jupiter in 1930 and 1974. Its [perihelion](#) distance has moved outwards by ~ 0.2 AU since 1941. This change in a relatively short period of time highlights the unstable nature of its orbit. The next close approach with Jupiter occurs in 2037, at a closer distance than the previous two interactions.

Sub-solar temperatures on the Centaur would vary between 160 to 170 K at its current distance (assuming it is a slow rotator). At low pressures, the change in temperature as the object rotates would be sufficient to trigger the [sublimation](#) of CO₂ ices.

To aid investigation of long-term behaviour, an extensive lightcurve was compiled from a variety of sources - the first, most complete and longest of its kind

this century, consisting of $> 65,000$ data points in different filters. Further analysis of this dataset is required to assess if activity intensity varies over time.

Chapter 8

29P/Schwassmann-Wachmann 1: Data Set

Due to the enormous coordination effort by Dr. Richard Miles with the [BAA](#)'s Mission 29P (Miles [2024b](#)), there are a huge number of images available of [29P/SW1](#), obtained by the [LCO](#) network, amateur astronomers, and by school students as part of the Comet Chasers programme (Usher [2025](#)). The [LCO](#) archive ([LCO Data Archive 2025](#)) contains over a decade of observations, with more available in an archive database.

8.1 Apparitions Analysed

A total of 9,581 images were obtained by the [LCO](#) network between May 2016 and July 2025, covering 9 apparitions of [29P/SW1](#). SDSS filter images (primarily r') were obtained over the 9 apparitions and a summary of these is given in table [8.1](#).

Overall, 3,356 days (9.2 years) separated the first and last datum in the dataset, with [29P/SW1](#) visible to the [LCO](#) network for 2,321 days (69.2% of the duration).

TABLE 8.1: Summary of apparition start and end dates, with length of apparition and number of observations made by the LCO network. Labels for each apparition are shown in the column ‘Apparition’, based on the year(s) the apparition spans.

Apparition	Start Date	End Date	Length	n Obs.
2016	2016-05-17	2016-11-24	191.2 d (0.52 yr)	725
2017	2017-03-21	2017-12-27	281.4 d (0.77 yr)	1,848
2018/19	2018-04-19	2019-01-13	268.3 d (0.73 yr)	675
2019/20	2019-05-13	2020-01-01	232.8 d (0.64 yr)	1,061
2020/21	2020-08-01	2021-03-20	231.0 d (0.63 yr)	791
2021/22	2021-07-20	2022-04-21	274.6 d (0.75 yr)	1,249
2022/23	2022-08-16	2023-05-14	271.0 d (0.74 yr)	1,123
2023/24	2023-09-12	2024-06-02	264.3 d (0.72 yr)	957
2024/25	2024-09-27	2025-07-24	300.5 d (0.82 yr)	1,152
Total	2016-05-17	2025-07-24	3,356 d	9,581

8.2 Dataset

Using the photometric pipeline developed and discussed in section 6, data obtained by the LCO network was processed and analysed from 2016-05-16 to 2025-07-24. This dataset mainly consists of g' , r' , and i' -band images, obtained from 0.4 m, 1 m, and 2 m telescopes in the LCO network. A smaller proportion of images were in Johnson-Cousins filters R, obtained from Skalnaté Pleso Observatory and the LCO network.

Overall, 12,083 images were processed, which corresponds to 5,565 data points following stacking of appropriate images. Not all this data was used in the final analysis, and the selection criteria are discussed in section 8.3. Following filtering, the final dataset presented here consists of 4,599 measurements.

TABLE 8.2: Summary of number of images from the LCO network, analysed using the photometric pipeline.

Filter	0.4 m	0.61 m	1.0 m	2.0 m	Total
SDSS g'	42	0	196	388	626
SDSS r'	795	0	1,530	884	3,209
SDSS i'	28	0	77	429	534
Cousins R	0	47	155	28	230

A summary of filters and telescope sizes are listed in table 8.2. Apparent magnitude lightcurves of each apparition can be seen in figures 8.1, 8.2, and 8.3, and $R(1, 1, 0)$ reduced magnitudes in figures 8.4, 8.5, and 8.6. Y-axis scaling is consistent for each subplot to highlight the differences in the size of the outbursts.

8.3 Data Quality

In total, 12,083 images (5,565 data points following stacking) were processed from the LCO archive and following an observing trip to Skalnaté Pleso Observatory.

Following initial processing of images using the pipeline detailed in section 6, it was apparent that it was not appropriate to use some images due to their poor quality or due to issues arising while processing. Table 8.3 displays a summary of issues occurring during this period. There are three main types of problem an image can exhibit: observing failure, rectifiable issues, and post-processing filtering. Examples of images with issues are shown in figure 8.7.

Observing failures are images of low quality due to poor/unfavourable observing conditions, telescope issues, or target tracking problems due to incorrect orbital parameters being used. These are unfortunately unavoidable and result in these observations being unusable - fortunately they are relatively few in number, just 680 in total. These images were often identified as problematic as they were hugely anomalous data points on the lightcurve, deviating significantly from

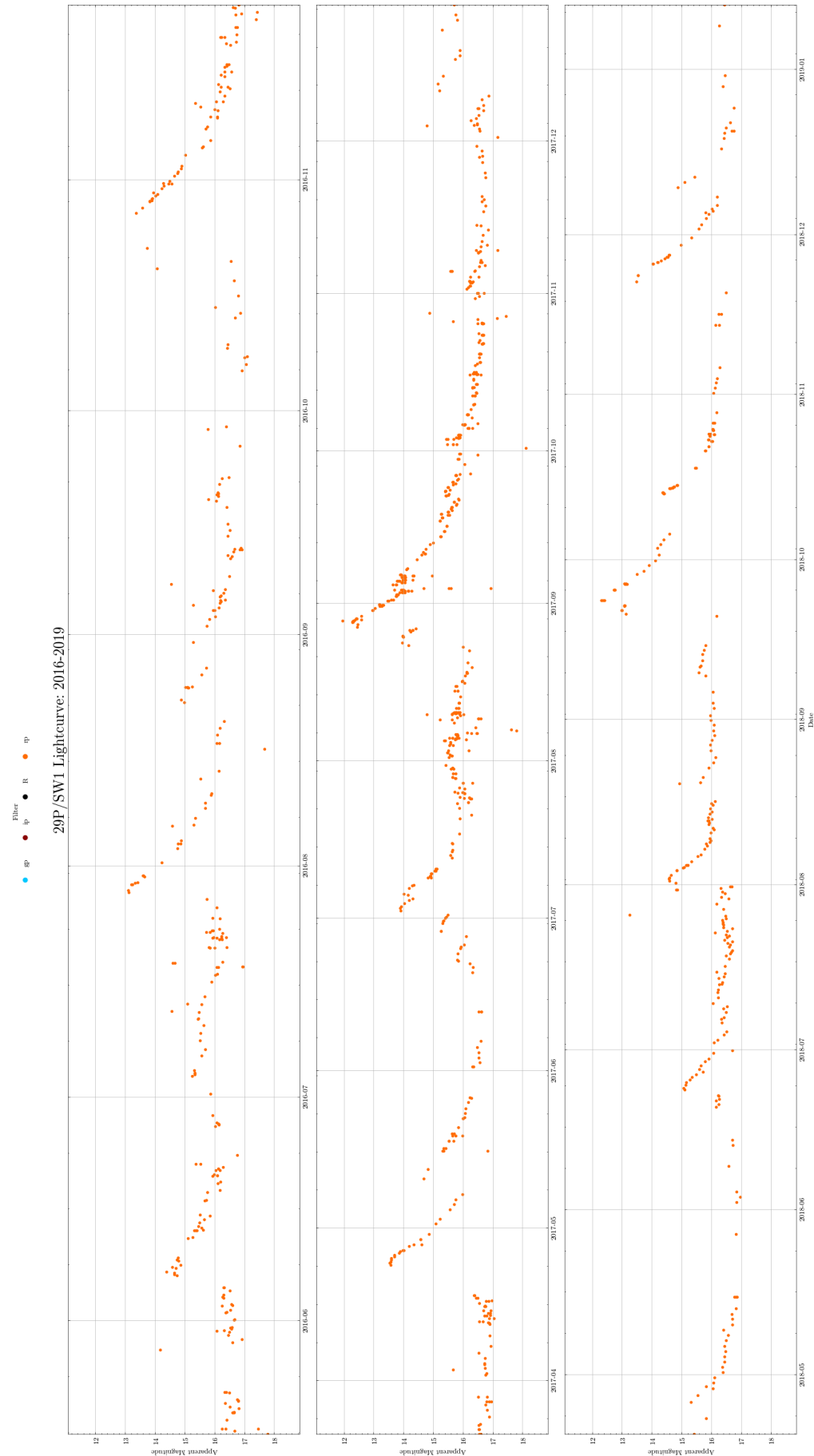


FIGURE 8.1: Apparent magnitude lightcurve of 29P/SW1 from 2016 to 2019.

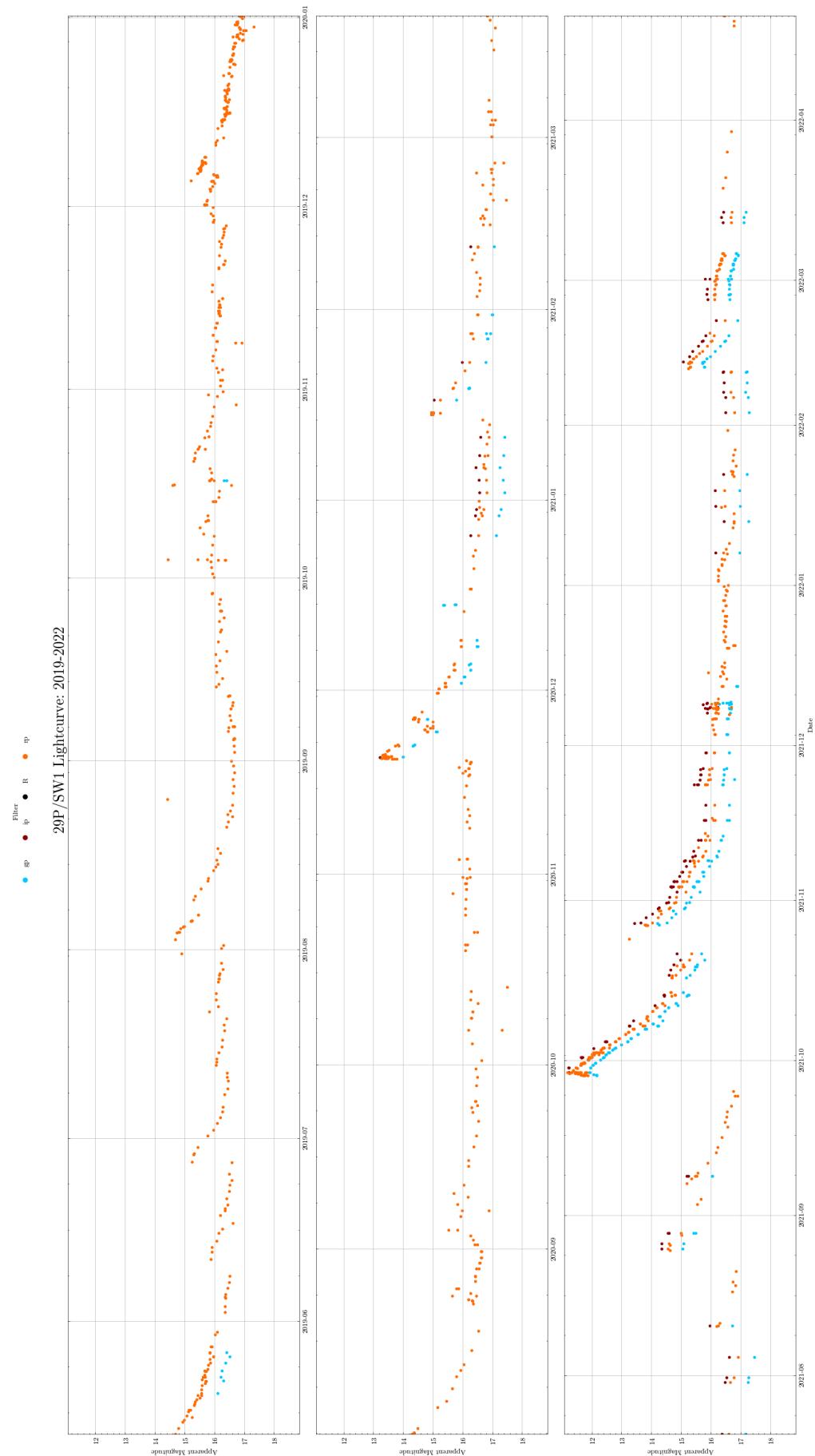


FIGURE 8.2: Apparent magnitude lightcurve of 29P/SW1 from 2019 to 2022.

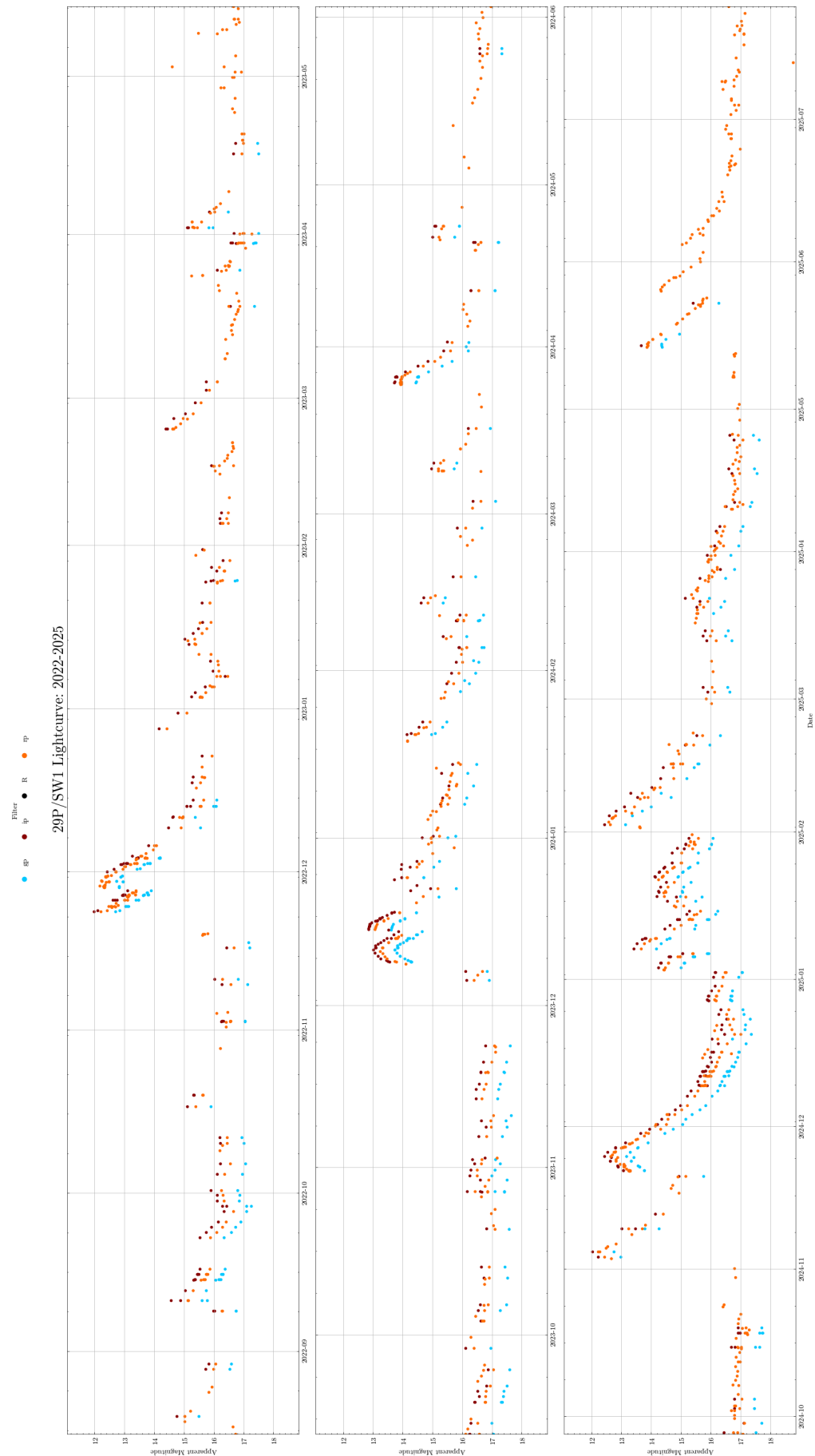


FIGURE 8.3: Apparent magnitude lightcurve of 29P/SW1 from 2022 to 2025.

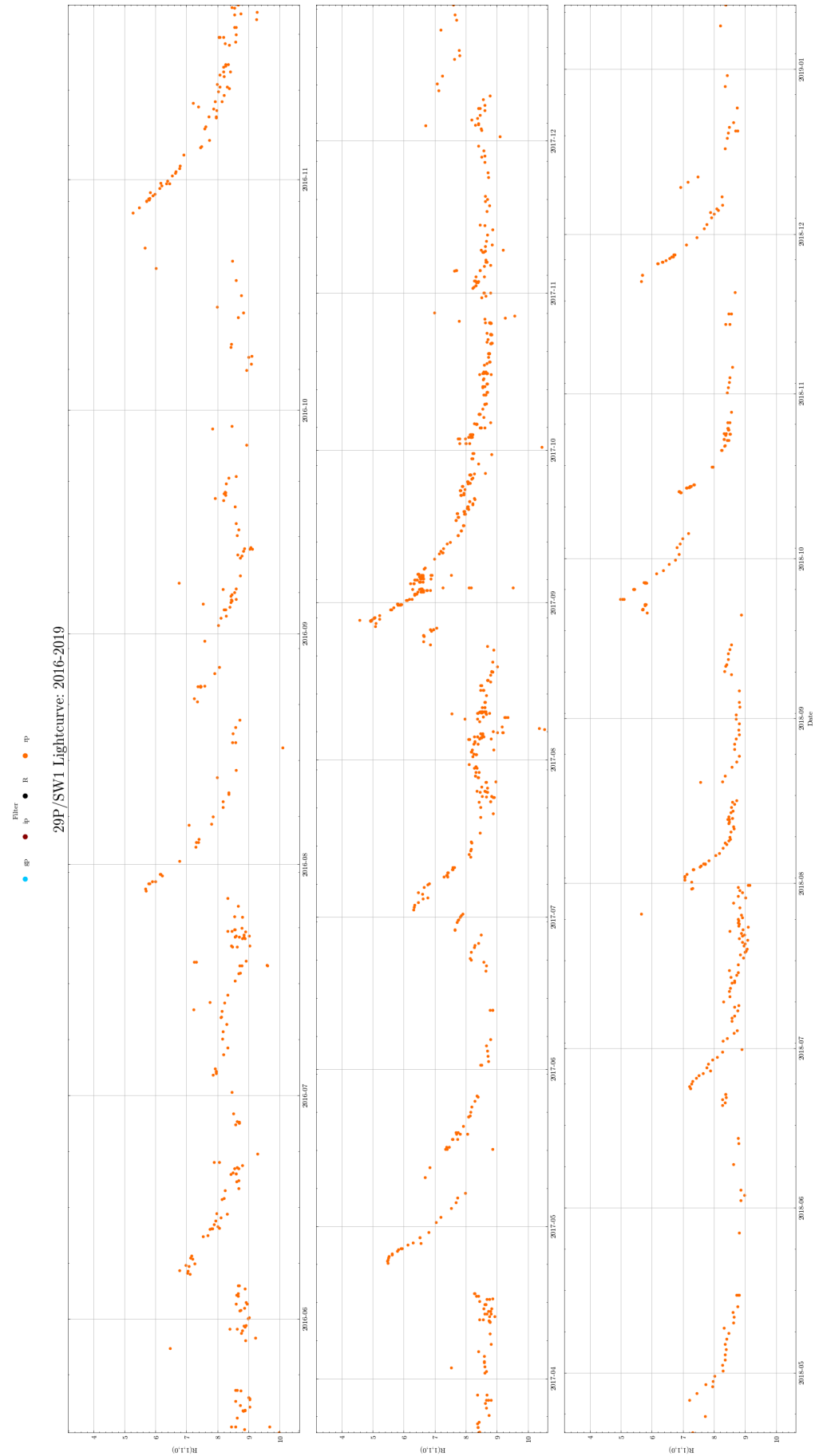


FIGURE 8.4: Reduced magnitude lightcurve of 29P/SW1 from 2016 to 2019.

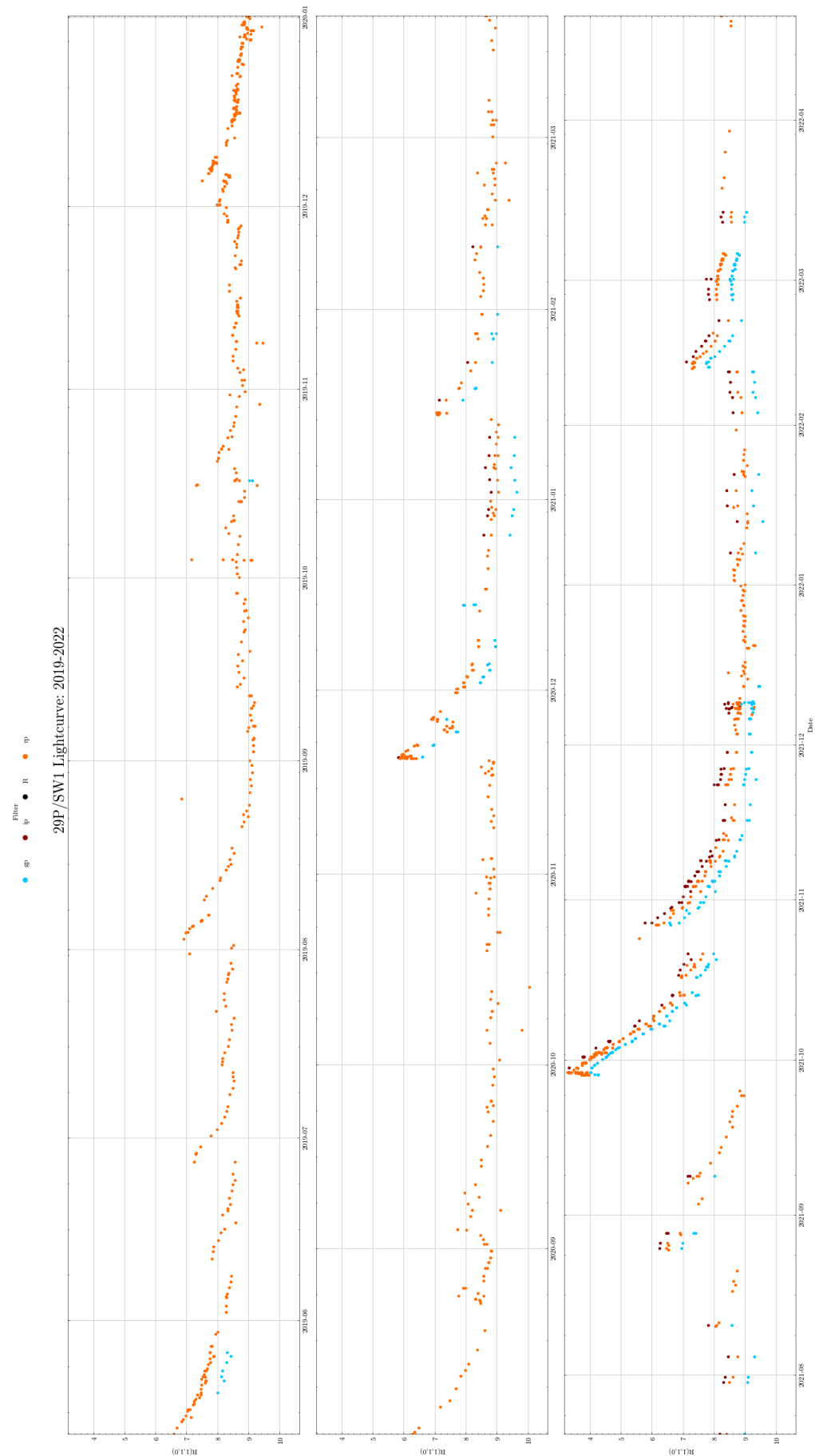


FIGURE 8.5: Reduced magnitude lightcurve of 29P/SW1 from 2019 to 2022.

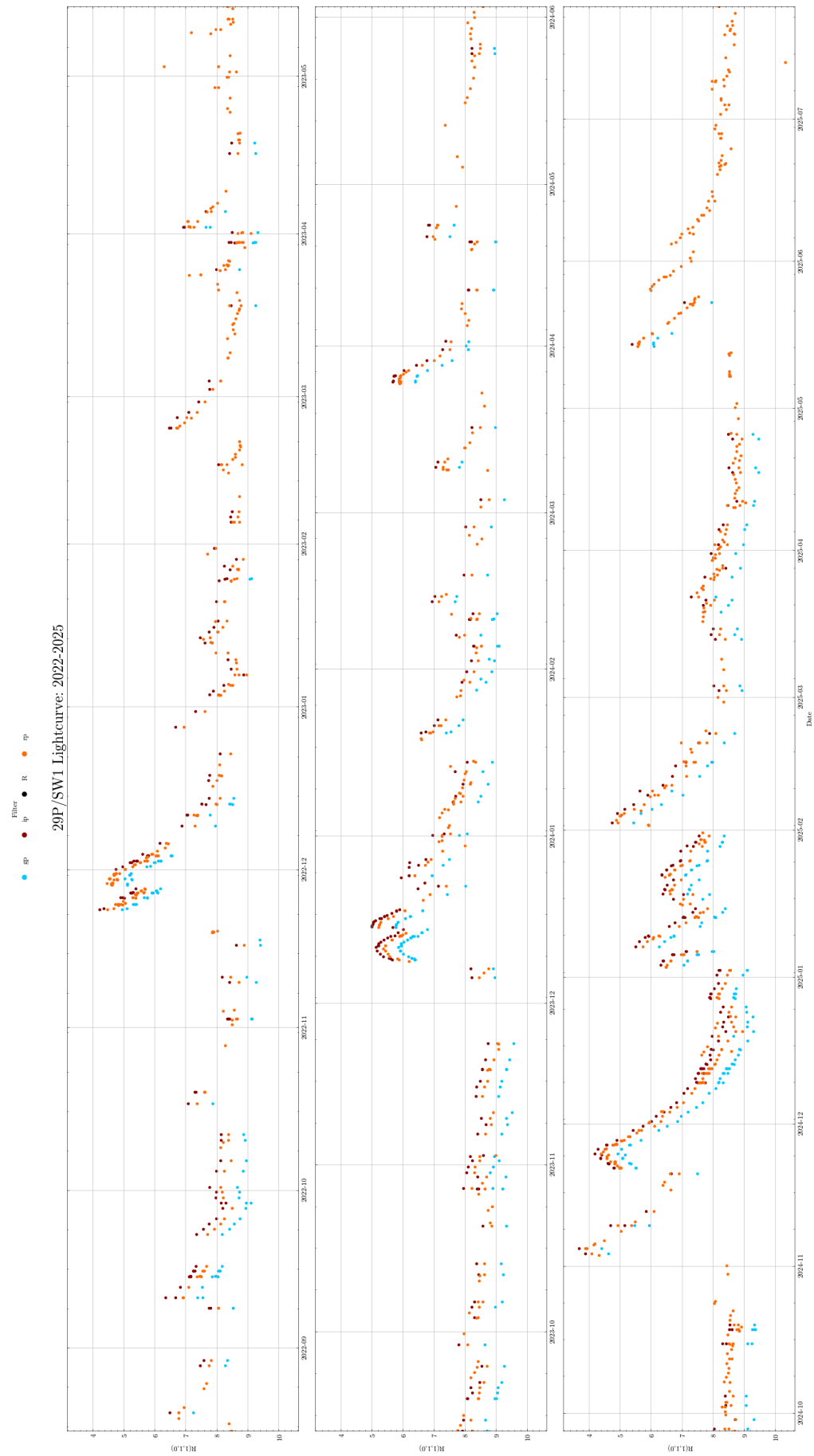


FIGURE 8.6: Reduced magnitude lightcurve of 29P/SW1 from 2022 to 2025.

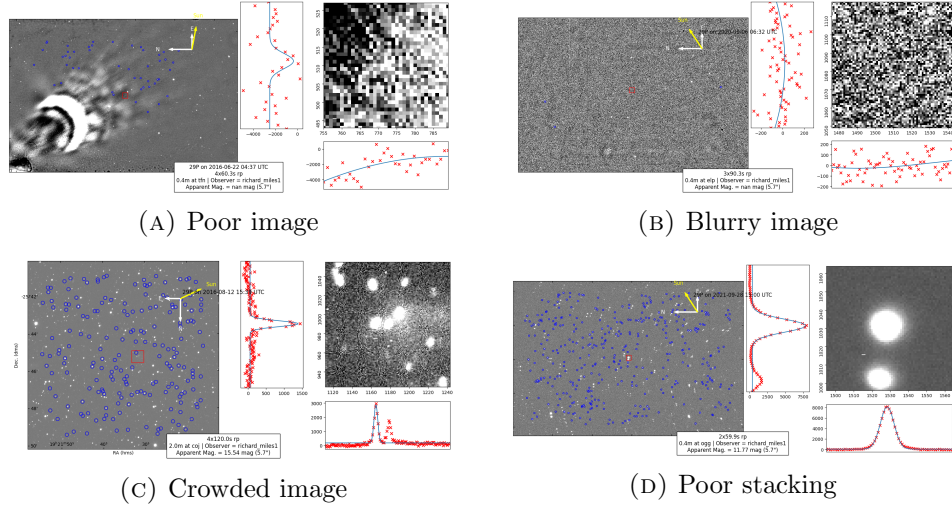


FIGURE 8.7: Examples of ‘bad’ images where they must be removed from the dataset or reprocessed to solve the issue.

the trend seen. It was important to identify these images accurately as an apparently ‘anomalous’ data point could be due to real changes in brightness. By looking at the corresponding summary image produced by the pipeline it would be immediately apparent if that datum had issues.

Rectifiable issues arise from pipeline limitations, such as alignment or stacking errors. These can be corrected by reprocessing with stricter target selection, and reduced number of images in a stack.

Following processing, we use parameters to filter the dataset to ensure the data is of the highest quality and reliability possible. Data was excluded if at least one of the following conditions are achieved: $SNR < 25$, apparent magnitude error > 0.1 mag, and number reference stars < 7 .

These parameters were chosen as they were towards the low/high end of their respective ranges, while also ensuring that $\lesssim 10\%$ of data points were excluded. Generally, observations had a very high signal-to-noise ratio, with mean $SNR \sim 550$, and maximum of $SNR \sim 6,000$. These values are in line with expected SNR values calculated using LCO’s Exposure Time Calculator (*Las Cumbres Observatory Exposure Time Calculator* 2025). The calculator gives an estimate

for the ‘worst-case SNR’ for a 60s exposure, using 0.4m SBIG telescope, SDSS-i’ filter, with airmass 1.5 during a full moon gives $\text{SNR} = 8$, when using the greatest measured apparent magnitude of 17.74 mag.

The upper estimate for a 60s exposure, using a 2m telescope and MuSCAT3 instrument, SDSS-r’ filter, with airmass 1.0 during a new Moon gives $\text{SNR} \sim 5000$, when using the smallest measured apparent magnitude of 11.18 mag.

Note that images may exhibit one, some, or none of these issues.

TABLE 8.3: Description of various issues affecting photometry. Note that ‘counts’ here refers to stacked images rather than individual raw images. Multiple issues may occur in a single stack, so totals do not sum to the number of stacks processed.

Issue	Count	Description
Observing Failures		
Blurry image	388	Highly pixelated image where it is difficult to resolve the target or stars.
Outside FOV	149	Incorrect orbital parameters used when requesting image.
Poor image	78	Artifacts present in image.
Crowded field	65	Nearby stars influencing target’s measured brightness.
Rectifiable Issues		
Poor stacking	35	Trailing or duplicate sources appearing in image.
Misaligned	19	Photometric aperture was not centred on the object’s nucleus.
Incorrect target	15	Pipeline incorrectly identified a nearby star as the target.
Post-processing Filtering		
Low reference star count	147	Too few stars resolved to be used as references.
Large error	48	Associated errors of apparent magnitude measurements exceeding a threshold value.
Low SNR	27	Highly pixelated or blurry image where it is difficult to resolve the target/stars.

We classified a ‘crowded field’ and stars within a 20” radius of the Centaur’s nuclear position. Although using a 5.7” aperture mitigates most contamination, the radial photometry is affected as nearby stars artificially brighten the comet. When stars which are not within a 20” radius from the nucleus but are overexposed, causing significant bleeding, are also considered to be in a crowded field.

Overall, the mean magnitude uncertainty with standard error is 0.003 ± 0.001 . The mean SNR and standard error is 540.9 ± 8.9 , with quartiles $Q_1 = 203.8$, $Q_2 = 330.1$, $Q_3 = 623.8$. Mean values listed for the remainder of this section have their associated standard error, calculated via,

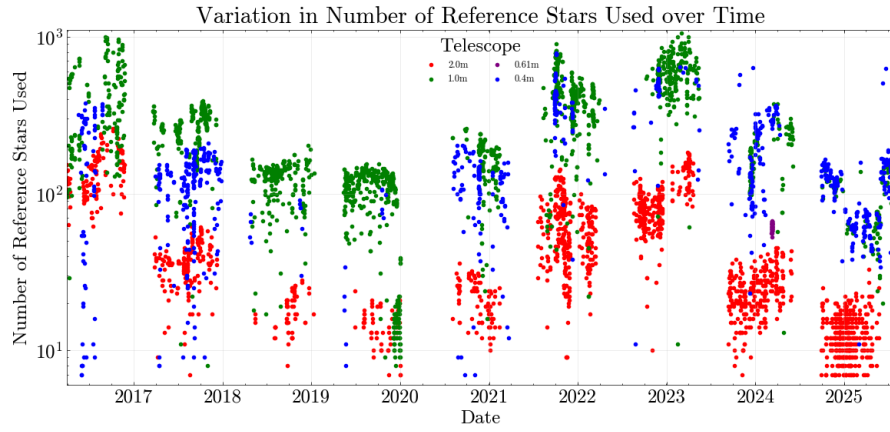
$$\sigma_{\bar{x}} = \frac{\sigma}{\sqrt{n}}$$

where $\sigma_{\bar{x}}$ is standard error, σ is standard deviation, and n is the number of observations.

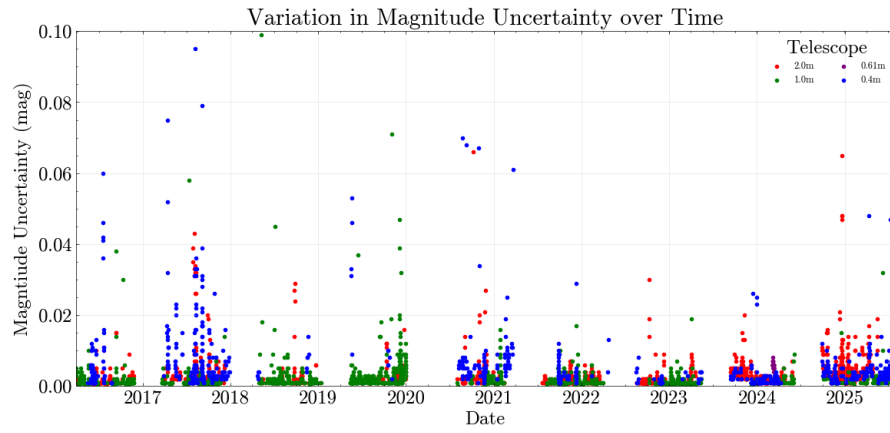
The number of reference stars used for photometric measurements varies over time, with a minima in the 2019/20 and 2024/25 apparitions, 70 ± 2 and 50 ± 2 , respectively, see figure 8.8a. This reduction is due to either 29P/SW1 passing into an area of sky with fewer stars, or an area which is not as well documented in the PanSTARRS 1 catalogue.

Images obtained with the 2.0m telescopes resulted in the fewest number of reference stars used for measurements due to its limited field-of-view, $n_{stars} = 45 \pm 1$. While 0.4m telescopes have the largest field-of-view, these images generally contain fewer reference stars, $n_{stars} = 180 \pm 5$, than images taken by 1.0m telescopes, $n_{stars} = 267 \pm 5$, taken at similar dates. For completeness, 0.61m telescope images have reference stars $n_{stars} = 62 \pm 1$, deviating from the trend as there are far fewer images available over only 2 nights’ observations. It is likely that the smaller telescope is unable to resolve dimmer stars that could be used as references, therefore resulting in a reduced number compared to the expected trend.

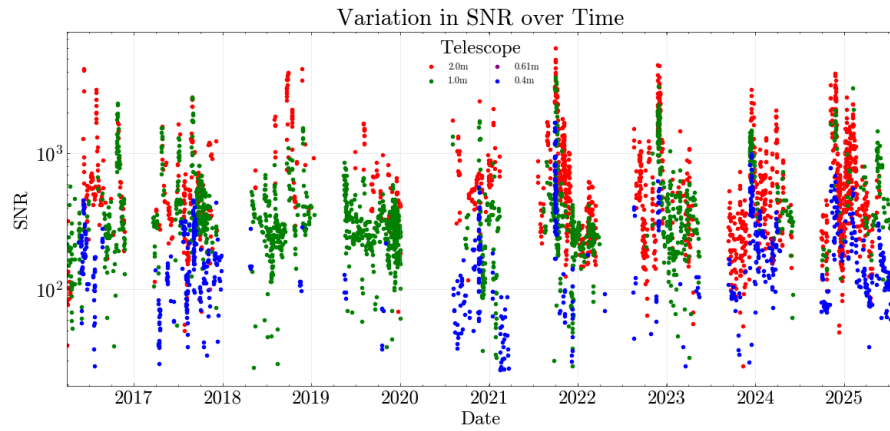
Magnitude uncertainties are generally consistent throughout the dataset (fig. 8.8b) with values clustered under 0.01 mag for all apparitions. It is clear that



(A) Reference stars used



(B) Magnitude Uncertainties



(C) SNR

FIGURE 8.8: Changes in reference stars used, magnitude uncertainty, and **SNR** over time for the whole dataset. Each colour represents a differing telescope size used for observations.

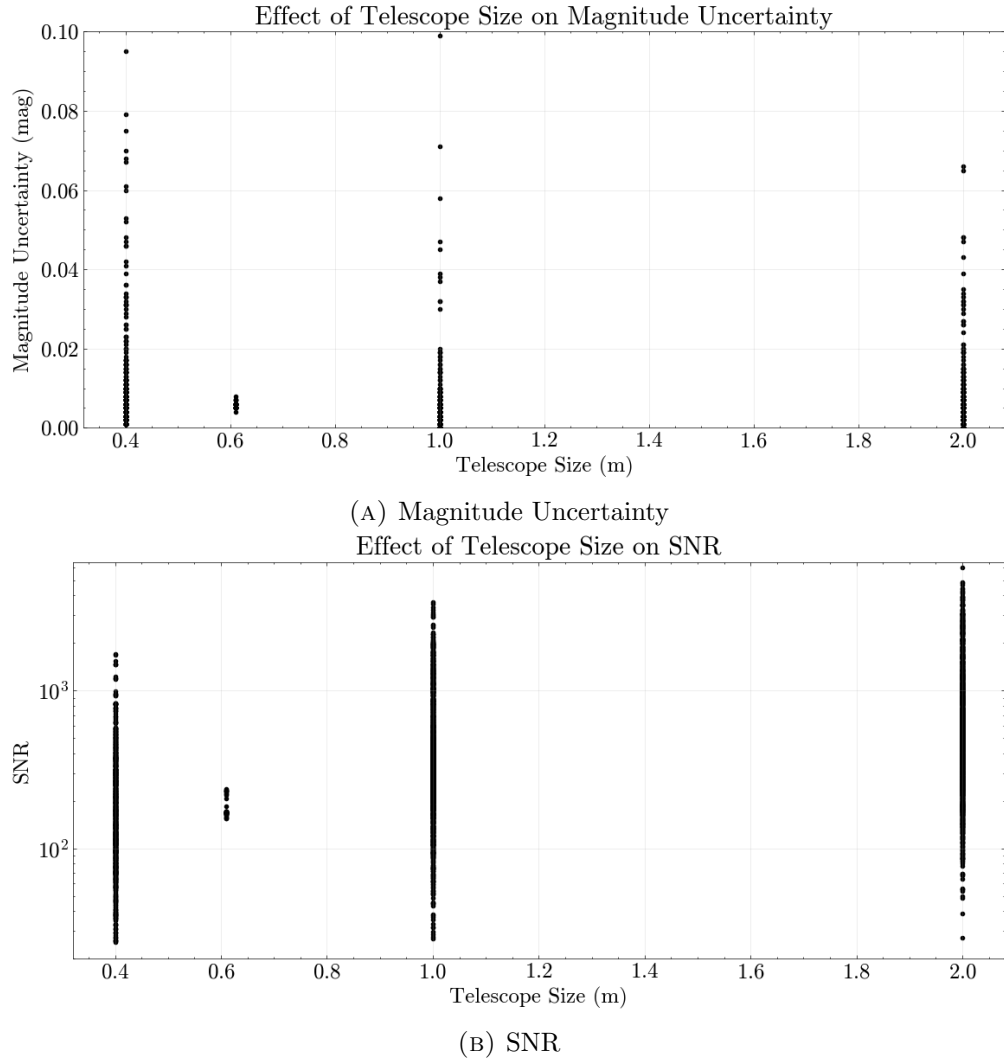


FIGURE 8.9: Influence of telescope size on magnitude uncertainty and [SNR](#).

0.4m telescope images have the greatest uncertainties, as expected given they have the lowest resolution of all the telescopes used. Trends in [SNR](#) over time reflects this, with the lowest [SNR](#) values for 0.61m and 0.4m telescopes (180 ± 4 and 230 ± 7 , respectively), figure 8.8c. While it would be expected that 0.61m images would have a larger [SNR](#) than the 0.4m, only 2 nights' worth of images were obtained for the 0.61m. The standard deviation would be smaller as observing conditions were far more consistent than those for the 9 years of 0.4m images. The 2.0m images have the greatest [SNR](#), $\text{SNR} = 800 \pm 18$, due to the high angular resolution for a small field-of-view, followed by 1.0m telescope images, $\text{SNR} = 460 \pm 10$. Comparison of magnitude uncertainties and [SNR](#) for each telescope size used are shown in figure 8.9.

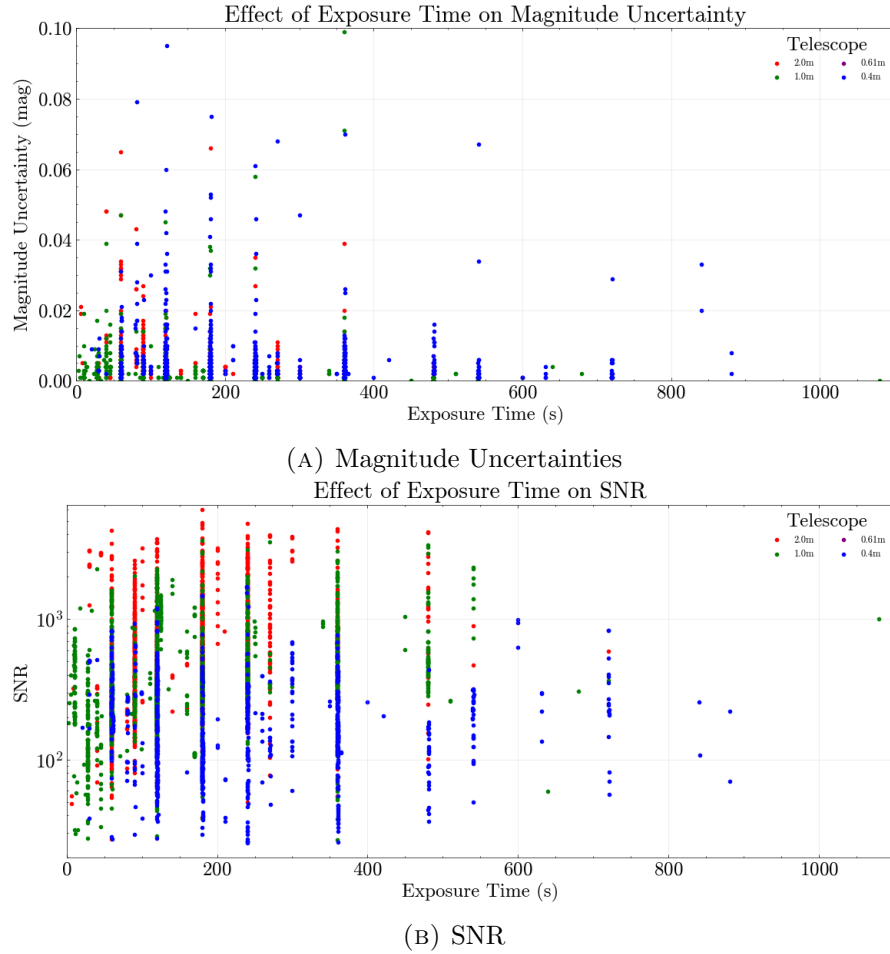


FIGURE 8.10: Effect of exposure time on magnitude uncertainty and [SNR](#). Each colour represents a differing telescope size used for observations.

Generally, the longer the exposure time of an image, the lower the scatter of uncertainties, with fewer large uncertainty values as is common at shorter exposures (fig. 8.10a). SNR does not necessarily follow this trend (fig. 8.10b). Higher [SNR](#) yields a more moderate distribution of [SNR](#), with a lower spread of values. The highest [SNR](#) occurs around 200s exposure time. Naturally, this could be biased due to far more observations having exposure times around 200s. Longer exposures of individual images are more prone to becoming overexposed, especially on the larger telescopes. This could have detrimental effects on the quality of the measurements made. So, 200s (or 3 to 4 image stacks of 60s exposures) is an optimal exposure time to maximise [SNR](#). Note, for exposure times of stacked images, the exposure of each image in the stack was summed.

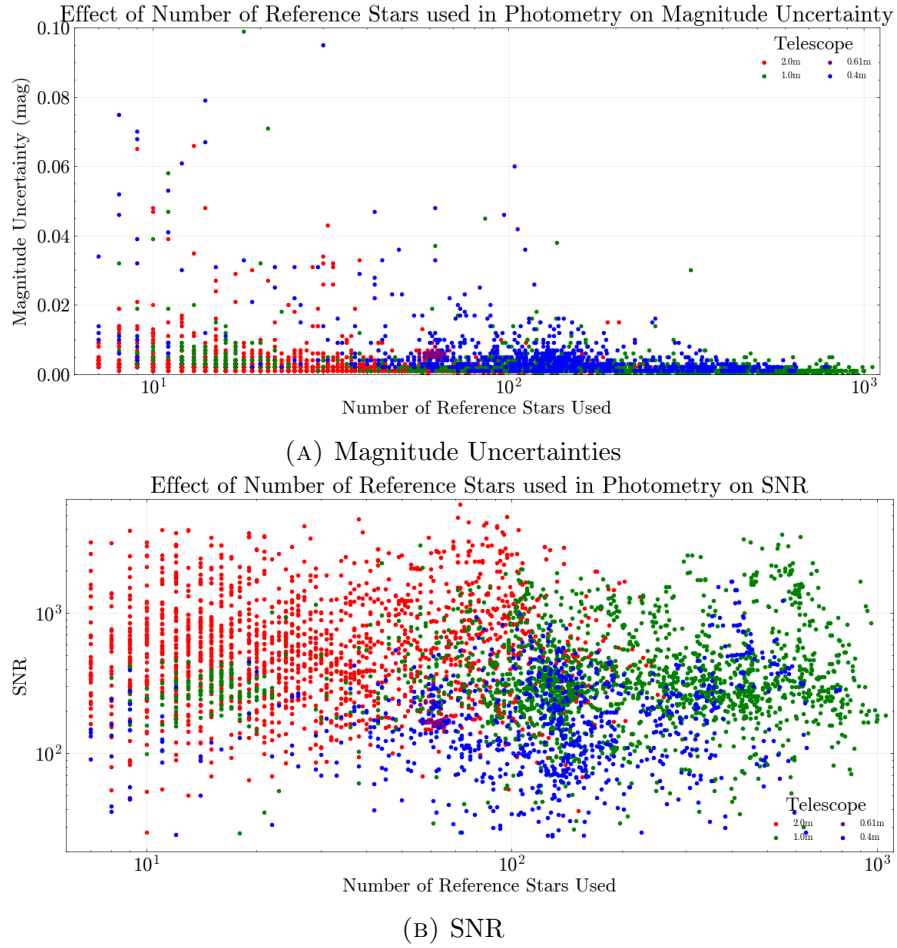


FIGURE 8.11: Influence of number of reference stars used on magnitude uncertainty and [SNR](#). Each colour represents a differing telescope size used for observations.

Measurements made with fewer reference stars resulted in generally greater uncertainties (fig. [8.11a](#)) while the upper end of reference stars used have far lower uncertainties with less spread. This is to be expected, as images which use fewer reference stars may not be the highest quality, thus the pipeline could struggle to identify the sources in the image. Fewer reference stars does not necessarily mean more uncertain measurements, but it does give an indication on the whole that these images are more likely to be of poor quality. This trend is not mirrored by the [SNR](#) completely, fewer reference stars have a similar range of [SNR](#) as most of the dataset, figure [8.11b](#), between 7 and 400 stars.

As [SNR](#) increases, the magnitude uncertainty decreases generally, with a far smaller standard deviation.

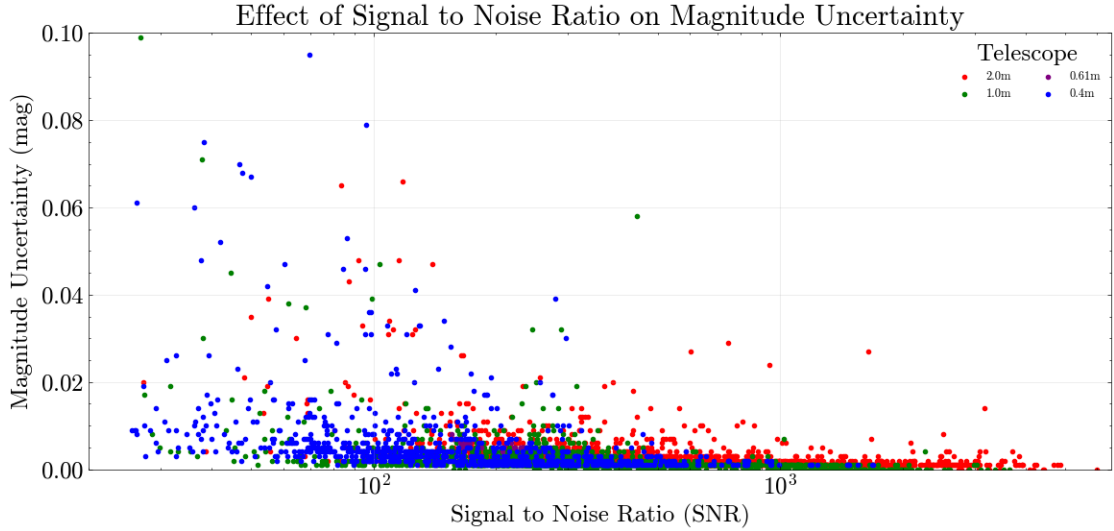


FIGURE 8.12: Relationship between SNR and magnitude uncertainty. Each colour represents a differing telescope size used for observations.

8.4 Quiescent Data

Given 29P/SW1's high cadence of outbursts, it is useful to distinguish data points which are part of the Centaur's active and quiescent periods. While investigating active periods of the dataset, it is useful to assess the frequency and anatomy of outbursts, the quiescent data is as important as it gives rare glimpses into the nucleus and the perpetual coma.

8.4.1 Lightcurve

To distinguish what is 'quiescent' for the Centaur, some assumptions must be made. Primarily, the synodic period of the object is fitted by eye based on the heliocentric and geocentric distances, and phase angles obtained from Giorgini and Yeomans (1999). To calculate this nuclear apparent magnitude, the following equation is used,

$$m_{nuclear} = 5 \log r + 5 \log \Delta + \alpha\beta + corr. \quad (8.1)$$

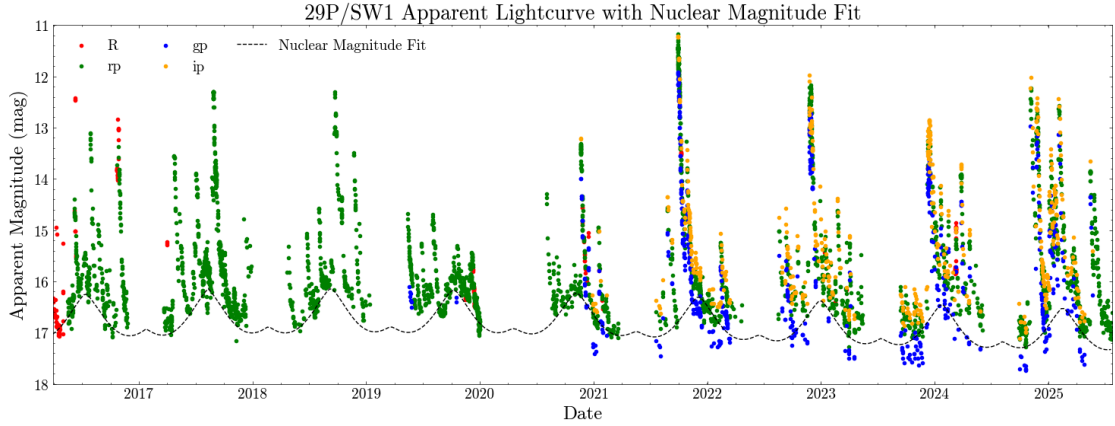


FIGURE 8.13: Synodic period fitted using orbital position data for 29P/SW1 overlaid on the lightcurve of the Centaur.

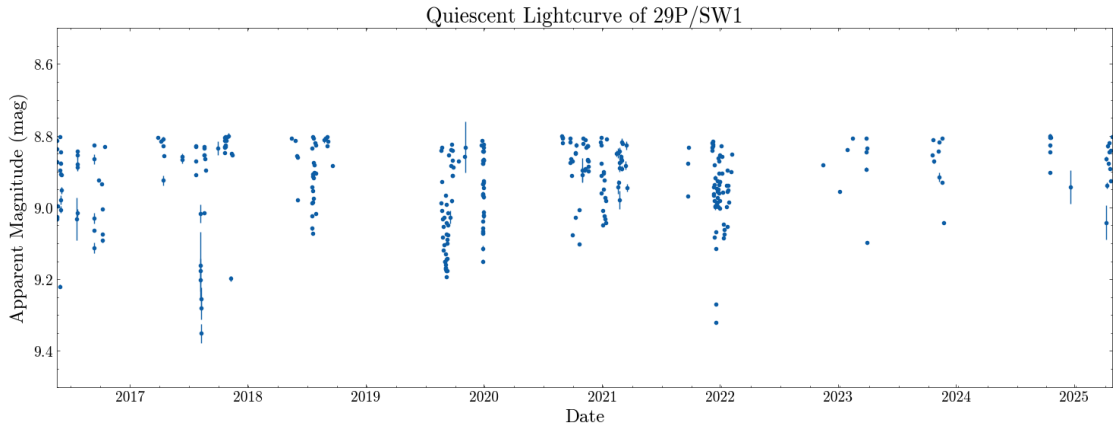


FIGURE 8.14: r' lightcurve of quiescent data of 29P/SW1.

where r is heliocentric distance, Δ is geocentric distance, α is the phase angle, β is phase correction (assumed to be $\beta = 0.035$), and $corr.$ is the correcting factor. The correcting factor is the parameter which is fitted ‘by-eye’. This was done by lining up the almost-sine curve of $m_{nuclear}$ with the visible variation seen at high magnitudes of the lightcurve, this fit is shown in figure 8.13.

The fit does not perfectly match the dataset, but it does give an estimate to the magnitude of the object when little to no activity occurs. To accommodate the poorness of this fit, data points which have magnitudes greater than $m_{nuclear} - 0.1$ were considered to be in a quiescent state, with the remainder being considered in an active state. Quiescent and active lightcurves in r' filter are shown in figures 8.14 and 8.15.

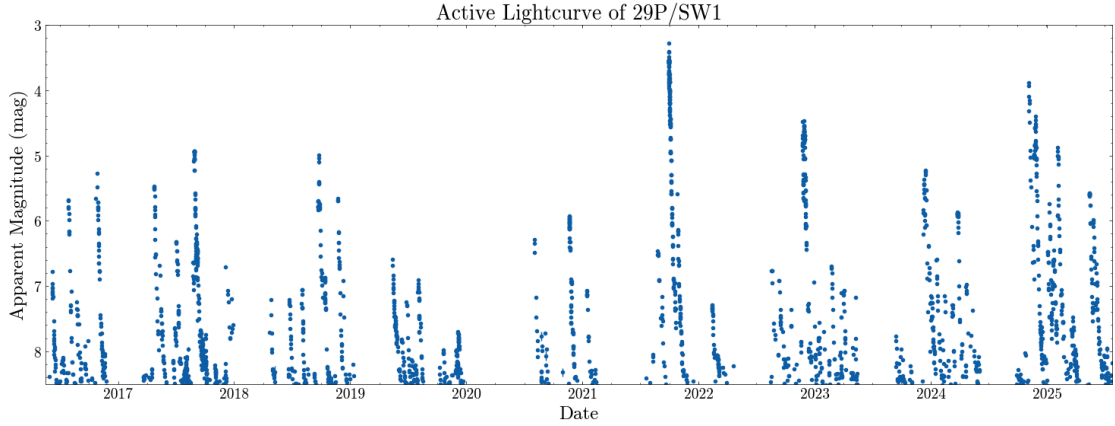


FIGURE 8.15: r' lightcurve of active data of 29P/SW1.

We can crudely estimate the proportion of time in which the Centaur exhibits active behaviour. In total, data was obtained on 1,514 days of the 3,355 day range between the start and end of the data, resulting in observations made on 45% of days. This proportion increases when we eliminate periods in which the object was visible, see sect. 8.1.

Eventually, 1,278 days were identified to lie solely in the active dataset, while 158 days lay in the quiescent dataset. An additional 78 days were identified to be where active and quiescent data were both present, days in which the brightness increases or decreases passed the threshold of $m > m_{nuclear} - 0.1$. From our dataset, 29P/SW1 is in an active state for 84% of the time, in a quiescent state for 10% of the time, and in a transitional state for 5% of the time.

8.4.2 Nuclear Magnitude and Radius

Identifying the quiescent dataset allows further investigation into these periods, showing how the nucleus and persistent coma radial profile varies. Plotting radial profile data for all quiescent data points, shows how the brightness measured changes as the aperture size is increased. A linear fit for measured magnitudes for aperture radii less than $\sim 25,000$ km was plotted to characterise the nuclear and inner coma environment. This straight line fit can be extrapolated to an aperture radius of zero as an estimate for the nuclear magnitude.

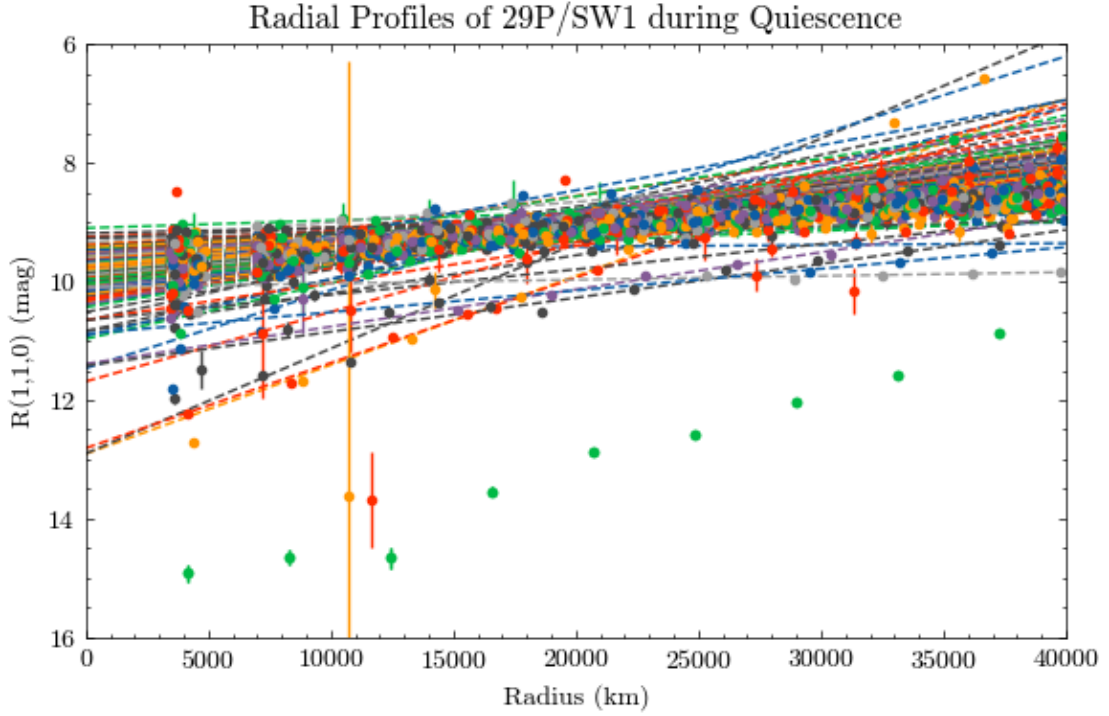


FIGURE 8.16: Radial profile of quiescent dataset. Straight line fits for radii < 2500 km are overlaid.

For the whole quiescent dataset, the radial profiles and line fits are plotted in figure 8.16.

To assess the quality of the straight line fit, the mean squared error was calculated.

$$MSE = (y_{data} - y_{fit})^2 \quad (8.2)$$

For each fit, this value is used as a proxy for the error to calculate the weighted mean of the nuclear magnitude. We use the weighing factor as,

$$w_i = \frac{1}{MSE_i} \quad (8.3)$$

with the weighted mean defined by,

$$\bar{m}_0 = \frac{\sum_i m_{0,i} w_i}{\sum_i w_i} \quad (8.4)$$

where m_0 is the nuclear magnitude. The standard deviation of nuclear magnitude was calculated using the *std* function from the NumPy package (Harris et

al. 2020) from each radial profile zero radius magnitude. A nuclear magnitude of $R(1, 1.0) = 9.68 \pm 0.41$ mag in the r' filter was calculated. Pereira et al. (2025) assumes the nuclear reduced magnitude to be $R(1, 1, 0) = 9.77 \pm 0.04$, with no filter used. Betzler (2023a) calculates the nuclear reduced magnitude to be $R(1, 1, 0) = 9.3 \pm 0.2$ and 9.10 ± 0.01 using ‘c’ and ‘o’ filters from the ATLAS survey.

Utilising eq. 3.15, this nuclear magnitude can be used to estimate the nuclear radius of 29P/SW1. Using an albedo of $p = 0.033 \pm 0.015$ (Bauer et al. 2013), we find a radius of $R_N = 37.3 \pm 11.0$ km, similar to values measured in publications by Schambeau et al. (2015), Schambeau et al. (2021), and Bockelée-Morvan et al. (2022).

8.5 Outburst Trends

MOEs comprise the majority of outbursts that the Centaur experiences. 73 of the 98 outbursts detected between 2016 and 2025 were part of a MOE. Comparing outbursts within a MOEs and Single-Outburst Events (SOE) shows that the mean change in magnitude of outbursts are similar, $\Delta m = 1.34 \pm 0.13$ mag and 1.31 ± 0.17 mag, respectively.

Despite this, outbursts within MOEs have a greater range of Δm than those in SOE, $\Delta m = 0.16$ to 5.58 mag and $\Delta m = 0.32$ to 3.17 mag, respectively. Of the 22 outbursts that occurred with $\Delta m > 2.0$ mag, 18 were part of a MOE, suggesting outbursts with greater intensity are more likely to occur in a MOE, as can be seen in figure 8.17. Interestingly, we also see 3 fairly distinct groups emerge regarding the intensity of outbursts, and so we use this to categorise the outbursts. These definitions will be used throughout this work.

$$\text{Minor Outburst : } \Delta m < 1 \text{ mag} \quad (8.5)$$

$$\text{Moderate Outburst : } 1 \text{ mag} \leq \Delta m < 2.5 \text{ mag} \quad (8.6)$$

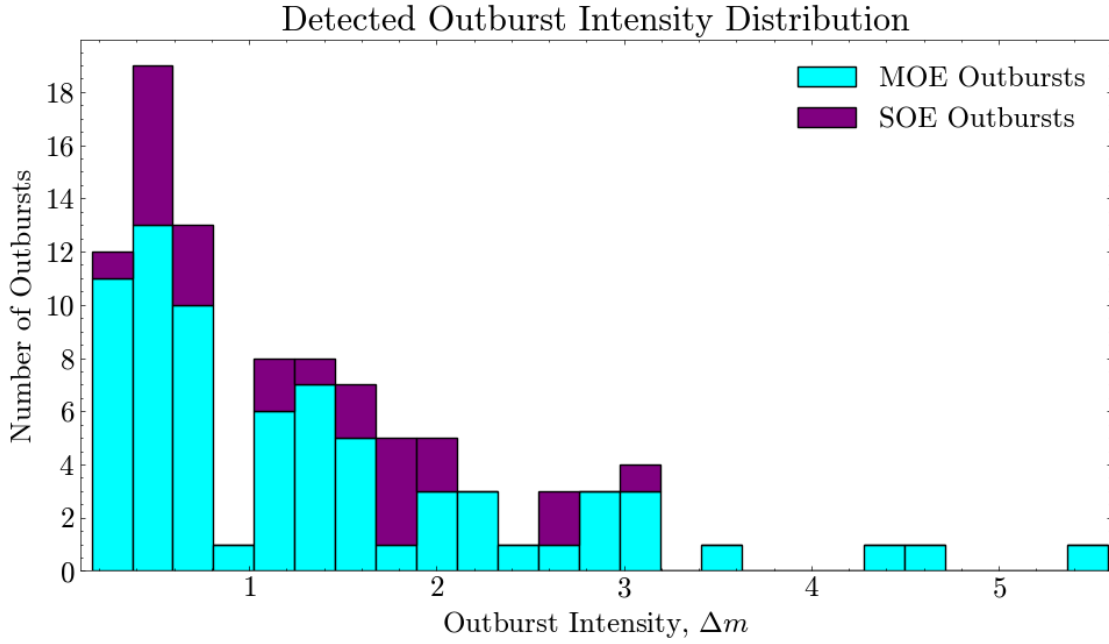


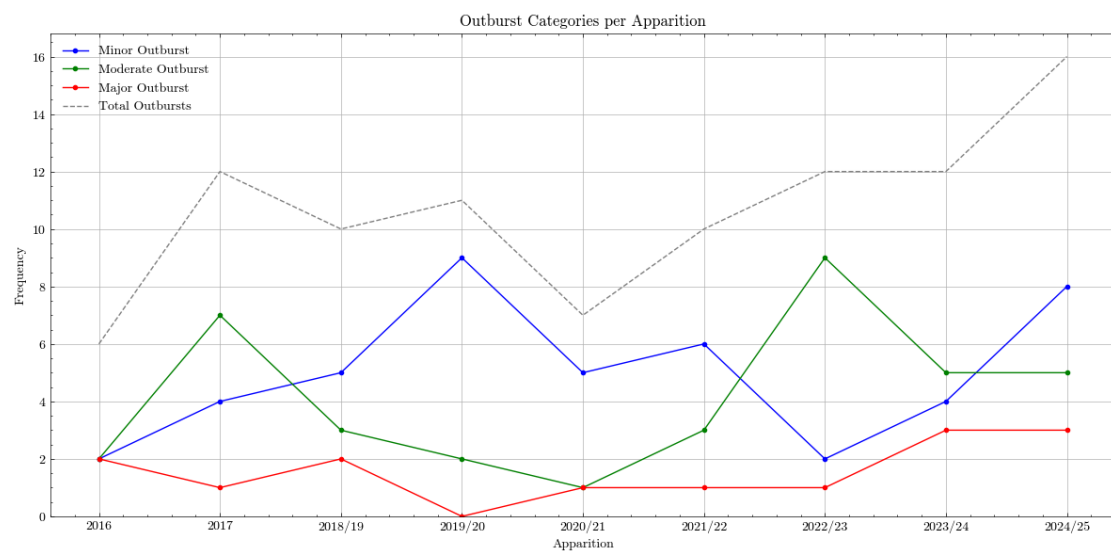
FIGURE 8.17: Histogram of outburst intensities. Minima can be seen around 1.0 and 2.5 mag, suggesting distinct outburst intensity groups.

$$\text{Major Outburst : } \Delta m \geq 2.5 \text{ mag} \quad (8.7)$$

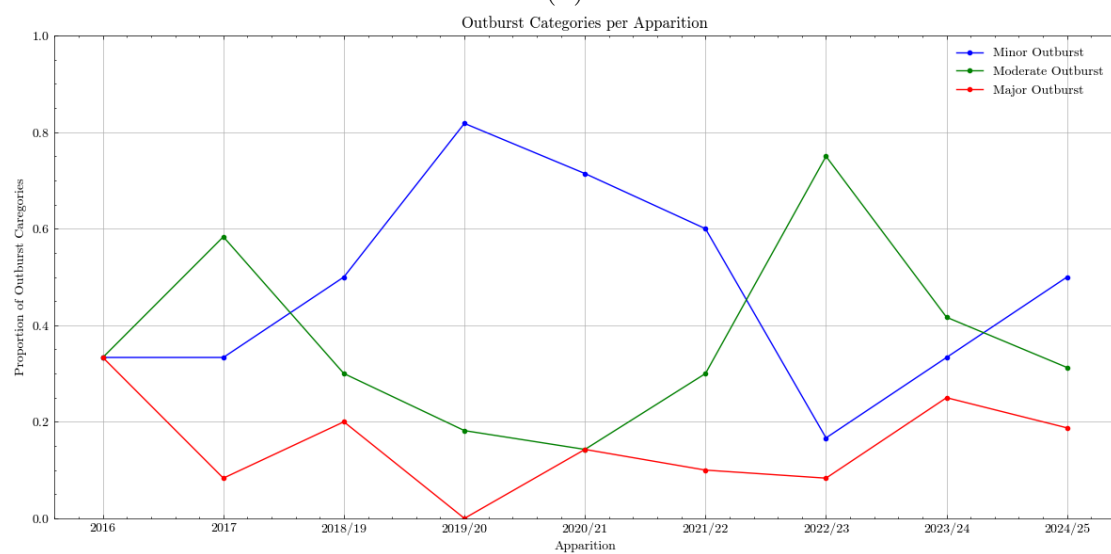
Table 8.4 shows the number of each category of outburst detected since 2016. Minor outbursts make up the majority of outbursts, closely followed by moderate outbursts. This is as expected, as major outbursts are likely to deplete the material which causes the events, thus fewer large outbursts can occur. Given this distinction, it is fair to assume that there could be several mechanisms (or combinations of mechanisms) driving these different categories of outbursts.

Average changes in magnitude for minor, moderate, and major outbursts are: $\Delta m = 0.50$ mag, $\Delta m = 4.58$ mag, and $\Delta m = 3.35$ mag, respectively.

We can see from fig. 8.18 that the proportion of minor, moderate, and major outbursts varies between apparitions. Minor outbursts dominate between 2018 to 2022, with over half of the outbursts during an apparition having $\Delta m < 1$ mag. Moderate outbursts make up the majority of outbursts between 2022 to 2024, with minor outbursts dominating in the 2024/25 apparition once again. No major outbursts occur in the 2019/20 apparition.



(A)



(B)

FIGURE 8.18: (A) Frequency of different categories of outbursts during each observed apparition. Major, moderate, and minor outbursts are shown in red, green, and orange, respectively. The total number of outbursts is represented by the grey dashed line. (B) Normalised version of (A) to show the proportion of each outburst category.

TABLE 8.4: Summary of number of different outburst types occurring during 2016 to 2025. Mean outburst intensity of each group is listed. It is not possible to categorise two outbursts as their start date occurs before an apparition begins, thus the surge is not calculable - these are classed as the ‘undefined’ outbursts.

Category	#	%	$\overline{\Delta m}$
Minor	45	45.9	0.50
Moderate	37	37.8	1.58
Major	14	14.3	3.35
Undefined	2	2.0	-

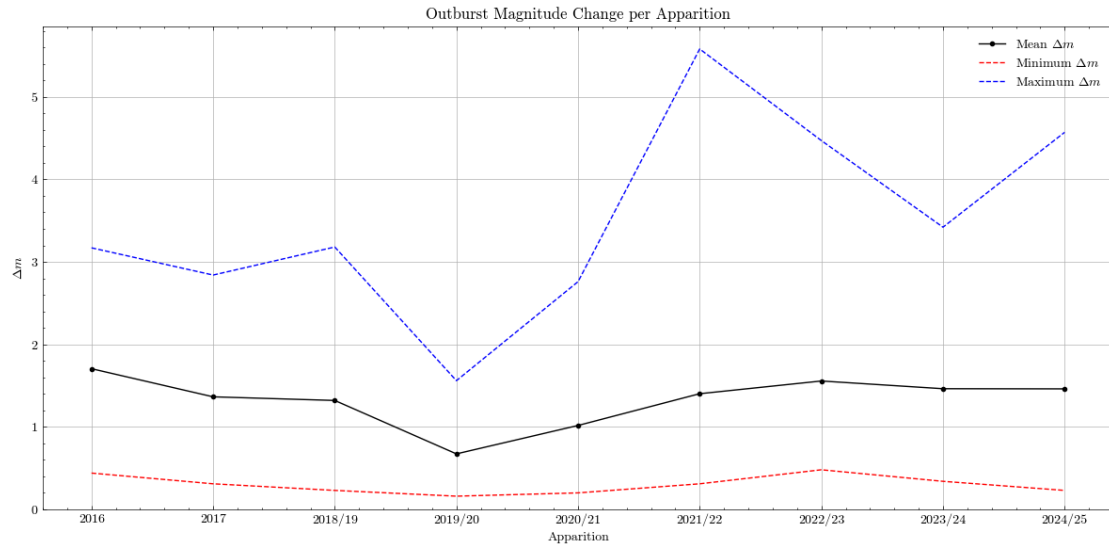
From this data, it is expected that 0 to 3 major outbursts occur per apparition. We see a maximum of major outbursts occurring in the 2023/24 and 2024/25 apparitions (3 major outbursts each), and a minimum of 0 outbursts in the 2019/20 apparition. The number of major outbursts generally increases from the 2019/20 apparition until the present day. This data suggests that the period observed could be a period of low major outburst activity, although more outburst data before 2016 and ongoing regular observations would be required to confirm this.

Corresponding to the lull in the major outburst numbers, there is also a decrease in moderate outbursts, reaching a low of 2 in the 2020/21 apparition. Between 2018 and 2022, no more than 3 moderate outbursts occur per apparition.

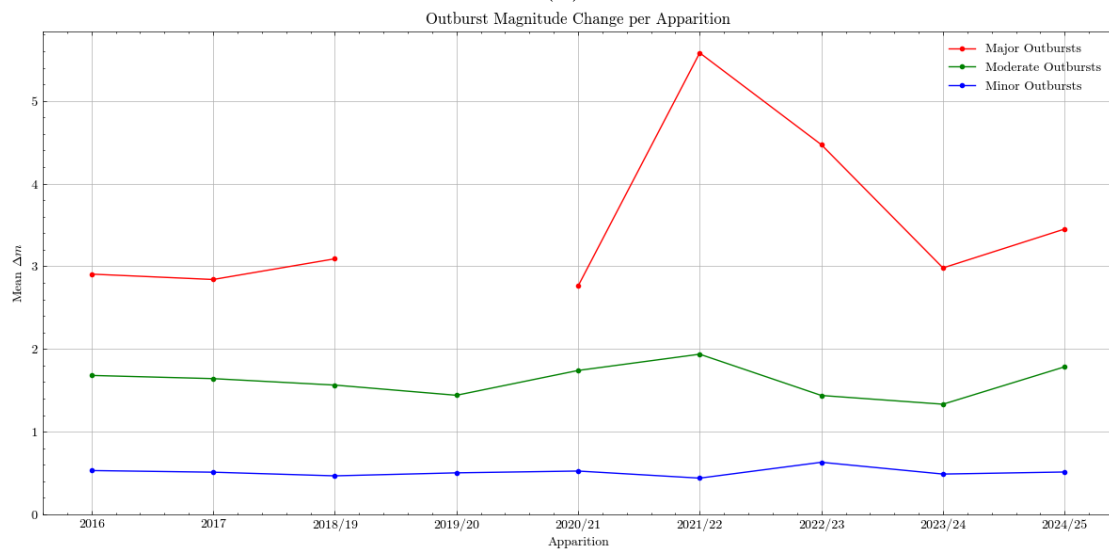
An equal number of all outburst categories occurs in 2016, although the dataset does not contain the whole apparition, therefore many outbursts may have been missed and not accounted for in figures 8.18. This appears to be confirmed by the total number of outbursts during this apparition.

Naturally, there are some caveats to these results. Sampling bias will affect the range of outburst intensities during [MOEs](#) as they are far more common than [SOEs](#). While we assume that [MOEs](#) occur due to the same source, it is entirely possible that two independent outbursts occur very shortly after one another.

The mean Δm of outbursts during an apparition does not vary greatly over the 9 observed apparitions, with its largest deviation in the 2019/20 apparition



(A)



(B)

FIGURE 8.19: (A) Mean outburst intensity per apparition, including maximum and minimum outburst intensities. The mean intensity of outbursts is fairly consistent over the 9 apparitions observed. A dip is seen at the 2019/20 apparition. (B) Mean outburst intensity per outburst category. Note that no major outbursts occurred during 2019/20 apparition hence why no data point is shown.

where zero major outbursts occurred. This mean increases slightly in the following apparition (2020/21), before it returns to a constant level from the 2021/22 apparition to present day. Despite the largest outburst of the dataset occurring in 2021/22 apparition, this does not affect the mean intensity greatly.

The most intense outburst occurred in the 2021/22 apparition with $\Delta m = 5.58$ mag, over 1 mag greater than the second largest outburst in 2024/25. While the maximum Δm decreases per apparition following this major outburst, the mean Δm does not drastically change, and in fact it increases in the 2022/23 apparition. The number of outbursts also increases following the 2021/22 apparition, including the number of major outbursts.

8.6 Outbursts

Outbursts are broadly described as surges in brightness of an object due to material being expelled from its nucleus.

Additional definitions are required to better characterise the activity seen in [29P/SW1](#). An outburst is classed as a sudden decrease in magnitude of greater than 0.1 mag which clearly deviates from the current trend of the object's brightness. We set the threshold of 0.1 mag as surges in brightness less than this are not as distinct from the 'normal' brightness of the Centaur due to variations in the measurements that may occur.

Another required definition is an *event*. An event is classed as a period of time in which one or more outbursts can occur, but the brightness only returns to its 'normal' level at the end of the event. For example, [MOEs](#) are, as expected, events in which numerous outbursts occur, with the subsequent brightness decay after an outburst being interrupted by an additional outburst. It is suggested that an outburst can trigger further outbursts, either by falling debris expelled during a previous outburst (Whipple [1980](#)), or due to changes in the nucleus

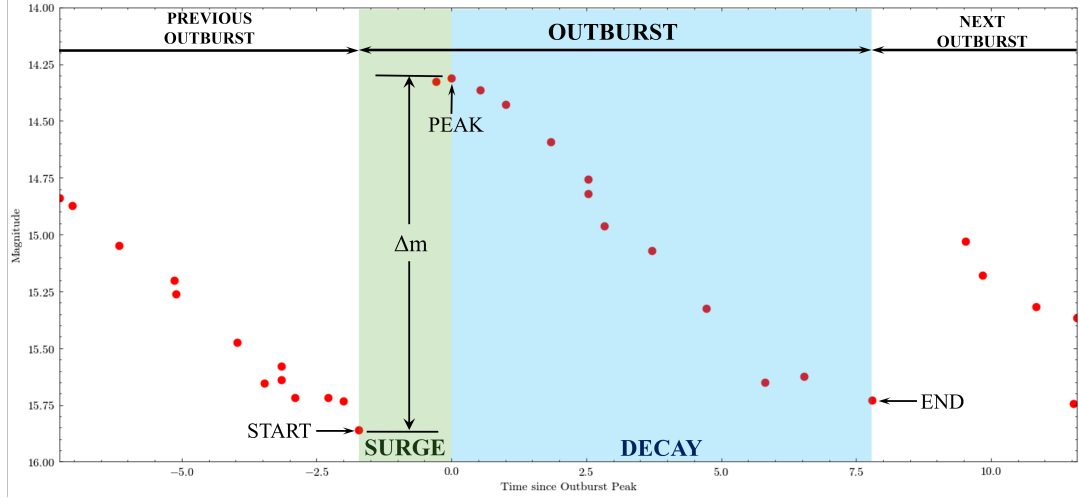


FIGURE 8.20: Diagram showing an example outburst. The start, peak, and end data points are labelled. The surge period is highlighted in green, also showing what is considered to be Δm for an outburst. Decay period is highlighted in blue when the magnitude increases again, either returning to a quiescent-level of brightness or onto the next outburst.

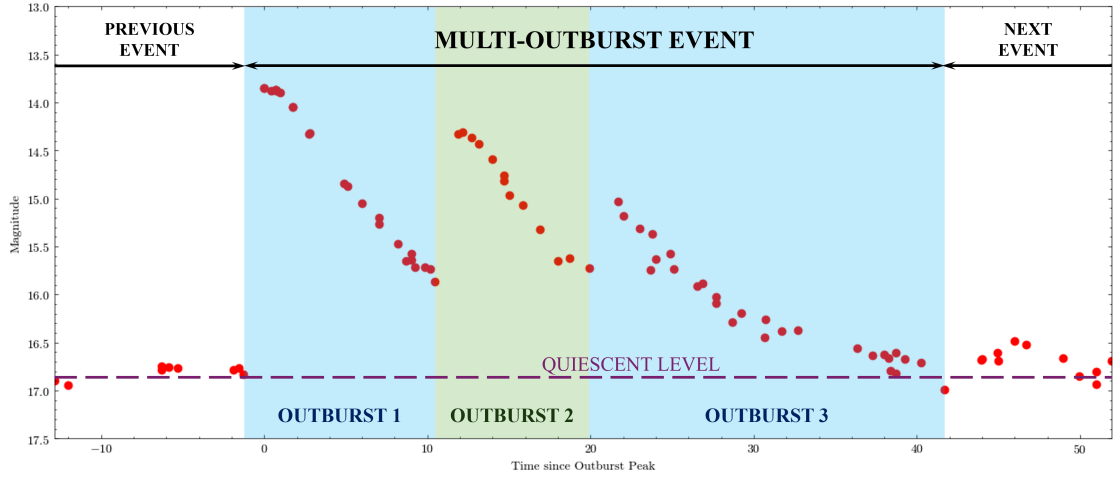


FIGURE 8.21: Diagram of a [MOE](#) showing that three outbursts occur before the brightness returns to its quiescent level.

structure via cave-ins or landslides after material is released from the nucleus (Lisse et al. [2022](#)).

Due to variations in the [geocentric](#) and [heliocentric](#) distances of the object over the course of its orbit, the apparent magnitude of the quiescent period (i.e. the nuclear magnitude) can be estimated using,

$$m_{r'} = 5 \log(r) + 5 \log(\Delta) + \beta \alpha + corr. \quad (8.8)$$

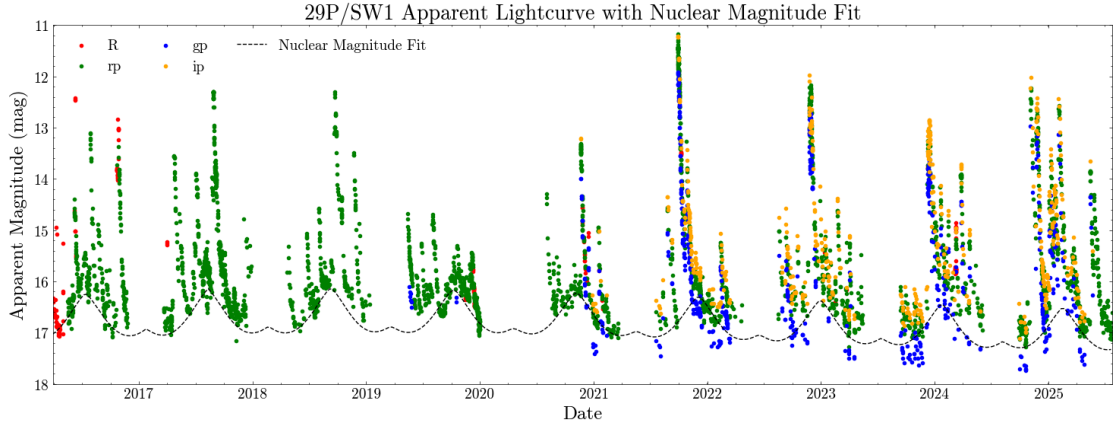


FIGURE 8.22: Lightcurve of 29P/SW1 with a nuclear fit estimation overlaid. This line was calculated using equation 8.8 with the *corr.* factor being adjusted by-eye to fit the r' dataset.

where r is heliocentric distance, Δ is geocentric distance, α is phase angle, β is the linear phase coefficient (assumed to be $\beta = 0.035 \text{ mag}/^\circ$), and *corr.* is a correction value which has been fitted by eye. The correction value was estimated to be $\text{corr.} = 8.9 \text{ mag}$ after adjusting this value to best fit the dimmer parts of r' filter in the lightcurve. This equation was used by Miles (2024b) for their measurements using the G filter. Figure 8.22 shows 29P/SW1's lightcurve with the nuclear magnitude plotted as a dashed line. This fit is to be used as a starting point to distinguish when the object is in quiescence or in an active period.

It is clear that there is a greater variation in subsequent measurements at fainter magnitudes, likely due to limitations with the photometry pipeline measuring dimmer objects. To identify when 29P/SW1 is in a quiescent period, we class all data with magnitudes $m > m_{\text{nuclear}} - 0.1$ as in quiescence.

Over the duration of the 9 apparition dataset, there have been observations made on 1,514 unique days, 45% of days of the whole time period, and 65% of the days within an apparition. Of those days, 1,356 (90%) were considered to be in an active state, i.e. observations with magnitudes less than 0.1 mag than the estimated nuclear magnitude from 8.8, and 236 (16%) were in a quiescent state. 78 days contained both active and quiescent data, thus causing both groups to overlap during a day. These values can be used as proxies for how much time the Centaur spends in either an active, quiescent, or transitional state (i.e. days

in which measurements show that the object is both active and quiescent). Removing days where both active and quiescent data is observed results in 1,278 (84%) active days, 158 (10%) quiescent days, and 78 (5%) transitional days.

Bockelée-Morvan et al. (2022), Lin (2023), and Wierzechos and Womack (2020) have suggested that a persistent coma exists surrounding the nucleus, even in periods when outbursts are not occurring. These results agree with this observation as it is clear the object does not spend an extended period of time in a quiescent state. This low-level activity may even be understated in my data as fitting the nuclear magnitude was done ‘by eye’ which naturally introduced additional errors. Perhaps the object is never in a state of [quiescence](#) and this fit only estimates the ‘normal’ constant activity the Centaur exhibits.

Python code was written to identify outbursts with $\Delta m > 0.4$ mag, identifying the start, peak, and end point of an outburst, noting the date and magnitude of each point. This code was fairly rudimentary and was not intended as a way to identify all outbursts perfectly. Outburst data was then assessed and compared with the detailed lightcurve of the period to check if the code had detected an outburst, or an error had been made due to anomalous data points, or an outburst had been missed entirely.

Outbursts with $0.1 < \Delta m < 0.4$ mag were included if it was clear that there was an initial surge in brightness and subsequent decay in brightness.

If there was uncertainty due to the scatter of the data points, the event was ignored - naturally leading to missed outbursts, but an unfortunate limitation of this analysis pipeline. Minor outbursts occurring around the nuclear magnitude of the Centaur would be most vulnerable to being missed as the scatter of the data points seen at this level is dimmer than at brighter magnitudes.

Comparing the number of detected outbursts in this dataset with those outbursts detected by Miles using data from the Mission 29P contributors, it is clear that numerous outbursts are missed due to the frequency of observations

obtained using the [LCO](#) network compared with imaging from amateur astronomers, who have more telescopes (but of smaller aperture) and a wider geographical distribution.

8.6.1 Outburst Anatomy

An outburst consists of 3 main points: the **start**, **peak** and **end**. For our purposes, the start of an outburst is defined as the data point where the observed trend begins to deviate from the decay pattern established by the previous outburst. The peak, easiest to define, is the brightest data point following a sudden increase in brightness. The end point is classed as the start point of the next outburst. Between these points are areas of great interest: the surge and decay periods. The surge is the period between the start and peak, while the decay is the period between the peak and end. Fig. [8.20](#) shows these points and regions on a lightcurve. These definitions were defined by the author to ensure consistency on characterising the outburst times.

Δm is the amplitude of the outburst in magnitudes. This is the decrease in magnitude from the start to the peak point. We are able to calculate the maximum surge time, $T_{surge-max}$, by measuring the time between the start and peak points. This is a maximum estimation of the surge time as we are limited by the observation cadence. If there are numerous data points during the surge period, a minimum estimation, $T_{surge-min}$, can also be made by measuring the time between the second and penultimate data points within the surge. Discussion of the surge can be found in sect. [8.6.3](#).

The decay time, T_{decay} is the time between the peak and end points of an outburst. This is the period in which the magnitude increases again due to the fading coma. It is possible to fit an exponential curve to this decay period. Discussion of the decay occurs in sect. [8.6.4](#).

Appendix [J](#) displays outbursts detected from 2016 to 2025 with their start, peak, and end dates and magnitudes listed. Each outburst is labelled according to the

apparition in which it appeared along with a letter for the order it occurred in during the apparition. Outburst labels with an additional number after the letter are part of a [MOE](#), where the final number represents the order in which the outburst occurred during an event. Mean values for each apparition are listed in table [8.5](#).

TABLE 8.5: Summary and mean values of outburst parameters per apparition.

Apparition	# per Apparition	# per Year	m_{start} (mag)	m_{peak} (mag)	m_{end} (mag)	Δm (mag)	Surge Rate (mag d ⁻¹)	Decay Rate (mag d ⁻¹)
2016	6	9.2	16.1 ± 0.1	14.4 ± 0.4	16.4 ± 0.3	-1.7 ± 0.4	-0.3 ± 0.1	0.1 ± 0.0
2017	12	15.6	15.7 ± 0.2	14.4 ± 0.3	15.7 ± 0.3	-1.3 ± 0.2	-0.4 ± 0.1	0.2 ± 0.0
2018/19	10	13.8	15.8 ± 0.4	14.5 ± 0.4	15.9 ± 0.4	-1.3 ± 0.3	-0.5 ± 0.0	0.1 ± 0.0
2019/20	11	17.3	16.2 ± 0.1	15.6 ± 0.1	16.3 ± 0.1	-0.7 ± 0.1	-0.1 ± 0.0	0.1 ± 0.0
2020/21	7	11.1	15.7 ± 0.4	14.7 ± 0.4	15.8 ± 0.5	-1.0 ± 0.3	-1.5 ± 0.1	0.0 ± 0.0
2021/22	10	13.3	16.4 ± 0.2	15.0 ± 0.5	16.4 ± 0.2	-1.4 ± 0.5	-0.1 ± 0.0	0.2 ± 0.0
2022/23	12	16.2	16.2 ± 0.3	14.7 ± 0.4	16.2 ± 0.3	-1.6 ± 0.3	-0.3 ± 0.1	0.1 ± 0.0
2023/24	12	16.6	16.1 ± 0.2	14.6 ± 0.3	16.0 ± 0.2	-1.5 ± 0.3	-0.2 ± 0.0	0.1 ± 0.0
2024/25	15	18.3	15.8 ± 0.2	14.3 ± 0.3	15.5 ± 0.3	-1.5 ± 0.3	-0.4 ± 0.1	0.2 ± 0.0
Mean	10.6 ± 0.9	14.6 ± 1.0	16.0 ± 0.1	14.7 ± 0.1	16.0 ± 0.1	-1.3 ± 0.1	-0.3 ± 0.0	0.1 ± 0.0

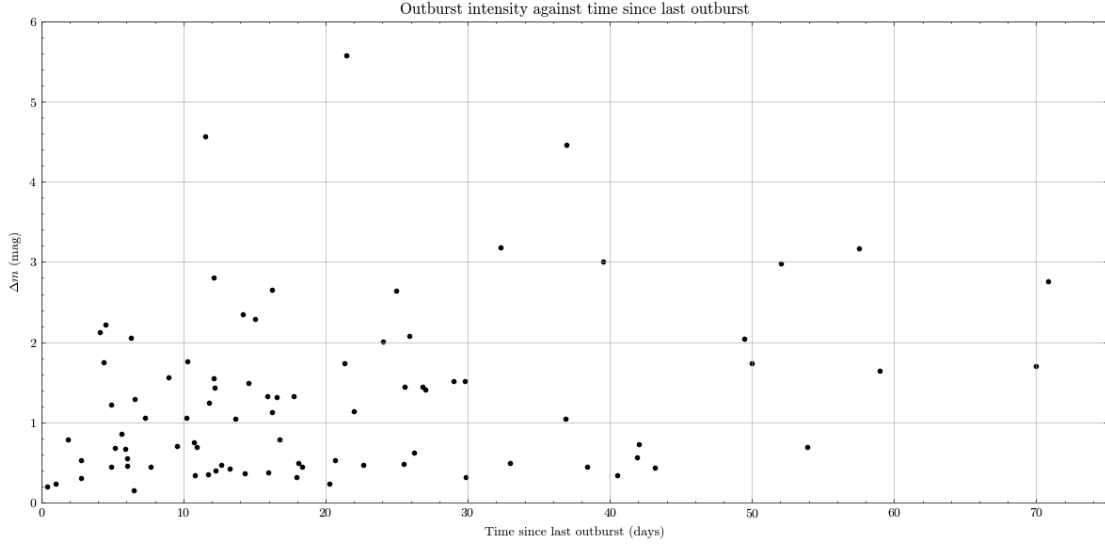


FIGURE 8.23: Relation between outburst intensity and time since the last outburst.

8.6.2 Outbursting Frequency

On average, 15.3 ± 1.0 outbursts with $\Delta m > 0.2$ mag occur per year, with 10.1 ± 1.0 occurring per apparition. The 2024/25 apparition had the largest number of outbursts (16), normalised to 19.5 in a year if the high-rate continues. A mean outburst amplitude for the whole dataset was $\Delta m = 1.33$ mag, with a peak $\Delta m = 1.70$ mag in the 2016 apparition (although it is important to note that the whole apparition is not available in the dataset), and minimum of $\Delta m = 0.67$ mag in 2019/20 apparition.

As stated above, on average, 10.1 ± 1.1 outbursts of $\Delta m > 0.2$ mag occur per apparition. Given that an apparition is not a whole Earth year, it is useful to normalise these values to a year. Thus around 14.1 ± 1.1 outbursts are expected each year. Trigo-Rodríguez et al. (2010) found 7.4 outbursts with $\Delta m > 1$ mag per year. Limiting our outburst data to the same amplitude criteria gives 7.9 outbursts per year, confirming the estimate of Trigo-Rodríguez et al. (2010). However, it is clear that variations occur from apparition to apparition.

No clear correlation is seen between outburst intensity and time since previous outburst, fig. 8.23. Smaller outbursts may occur at a shorter time after an outburst, although this could be sampling bias.

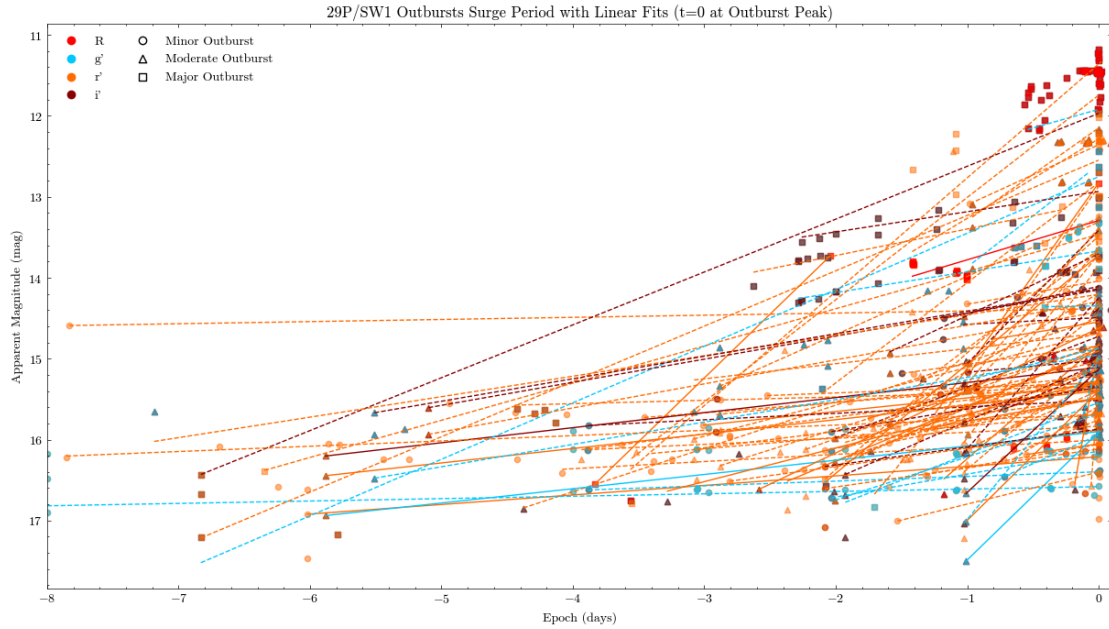


FIGURE 8.24: Surge period lightcurve of overlaid outbursts including straight line fits.

8.6.3 Surge Rate

The surge period is the first part of an outburst, where the brightness suddenly increases over a short period of time. Specific definitions are provided in sect. 8.6.1. It is important to note that the measured time for the surge to occur will not be the precise surge time, as we are limited by the observation cadence.

Outburst lightcurves were overlaid such that $t = 0$ at the peak of the outburst. This allows investigation into how the lightcurves of outbursts vary. Straight lines were fitted to the surge period to measure the change in magnitude over time. Figure 8.24 displays the surge period and fits.

It is clear that the surge gradient varies greatly between outbursts. This is to be expected as outbursts exhibit a wide range of different intensities. Figure 8.25 compares the relation between the surge gradient and the outburst's intensity. Little relation can be seen between these parameters, with a large scatter. This plot does show that the surge gradient for the same outburst in different filters does vary, suggesting that there is indeed a change in colour as the brightness increases.

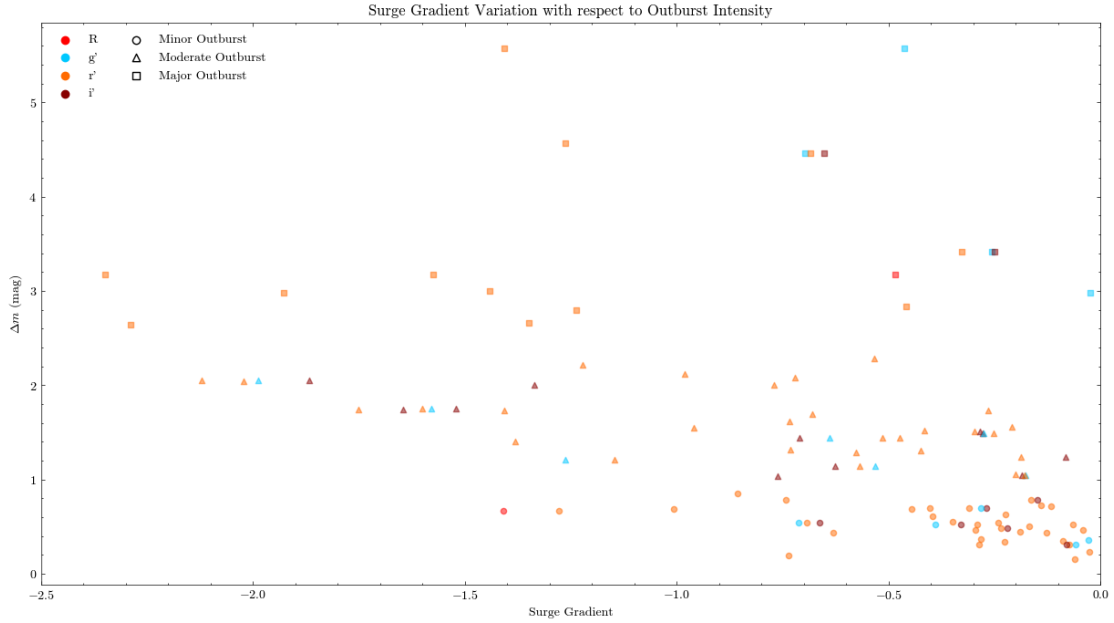


FIGURE 8.25: Relation between the surge gradient and outburst intensity.

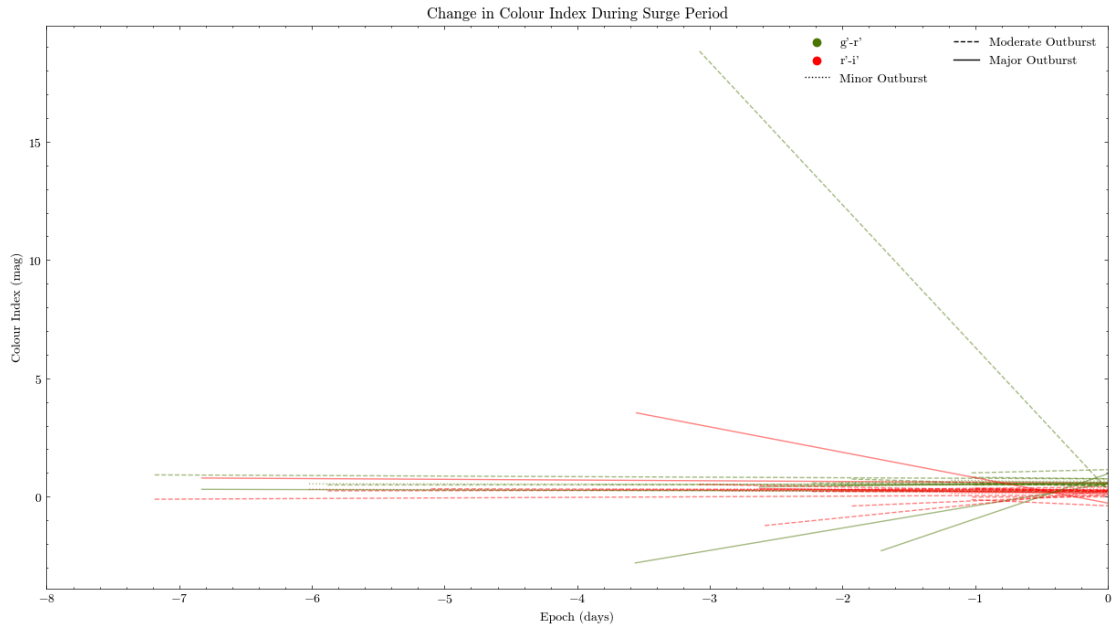


FIGURE 8.26: Change in colour indices during surge period of an outburst.

The colour index of the surge period was calculated using the linear fits made, and subtracting the corresponding value for a given epoch. This colour fit remains fairly constant from the onset of the outburst until the peak, fig. 8.26.

The gradients are calculated by subtracting one filter's gradient from another. Figure 8.27 plots $g' - r'$ and $r' - i'$ gradients against outburst intensity. The colour index gradient is centred around 0, suggesting that the surge gradient is

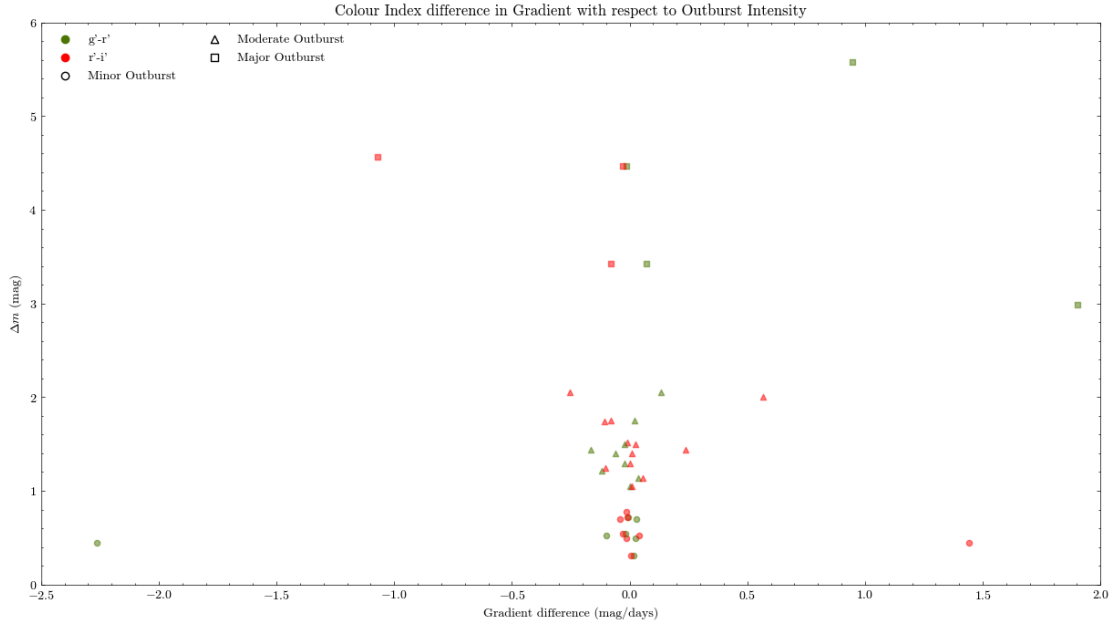


FIGURE 8.27: Surge gradient for one filter subtracted from that of another is plotted against outburst intensity.

TABLE 8.6: Mean surge gradient in multi-band observations. Change in colour indices is listed.

Filter	Surge Gradient (mag d ⁻¹)
g'	-1.58 ± 1.25
r'	-0.89 ± 0.63
i'	-0.72 ± 1.26
R	-1.83 ± 1.28
$\Delta(g' - r')$	-0.25 ± 0.30
$\Delta(r' - i')$	-0.01 ± 0.08

fairly consistent between filters. Some scatter occurs for the more intense outbursts.

We calculate the mean surge gradient for each filter and colour index. Table 8.6 summarises these values.

The gradient increases, becoming less steep as the filter wavelength increases - the $g' - r'$ colour index decreases over time at a rate of -0.25 ± 0.30 mag d⁻¹, while the $r' - i'$ remains fairly constant, with a rate of -0.01 ± 0.08 mag d⁻¹.

8.6.4 Decay Rate

Crudely, the decay rate is calculated by,

$$\text{Decay Rate} = \frac{m_{\text{peak}} - m_{\text{end}}}{T_{\text{decay}}} \quad (8.9)$$

where m_{peak} and m_{end} are the peak and end magnitudes, respectively, and T_{decay} is the decay time, these are defined in sect. 8.6.1.

This rate is an approximation of how the object decays in brightness as it is better approximated by a function. The rate of decay varies throughout the decay period, with a steeper dimming occurring shortly after the peak, and plateaus over time. This value would be skewed by outbursts as part of a MOE as the decay profile would appear steeper as a new outburst would occur before the exponential decay can plateau. Regardless, this approximation can be used as a surface level comparison of outburst decay periods.

The normalised flux decay period is shown in fig. 8.28, with the outburst types separated in fig. 8.29. These plots have been normalised by dividing the flux with the maximum flux for a given outburst. This allows the outburst peak to be at 1, to observe if decay rates vary due to outburst intensity, or if it decays at the same rate. Note: it is possible that the peak of the outburst was not observed, therefore it would not be fully representative of the outburst.

Investigation into calculating a fit of the decay period in magnitudes was conducted, this resulted in fairly variable and temperamental results which did not fit all decay periods well. It was decided to fit the flux values rather than magnitude. Analysis of the initial method can be found in appendix K.

The magnitude values were converted into flux to better fit the data using an exponential decay using,

$$F = 10^{-0.4m} \quad (8.10)$$

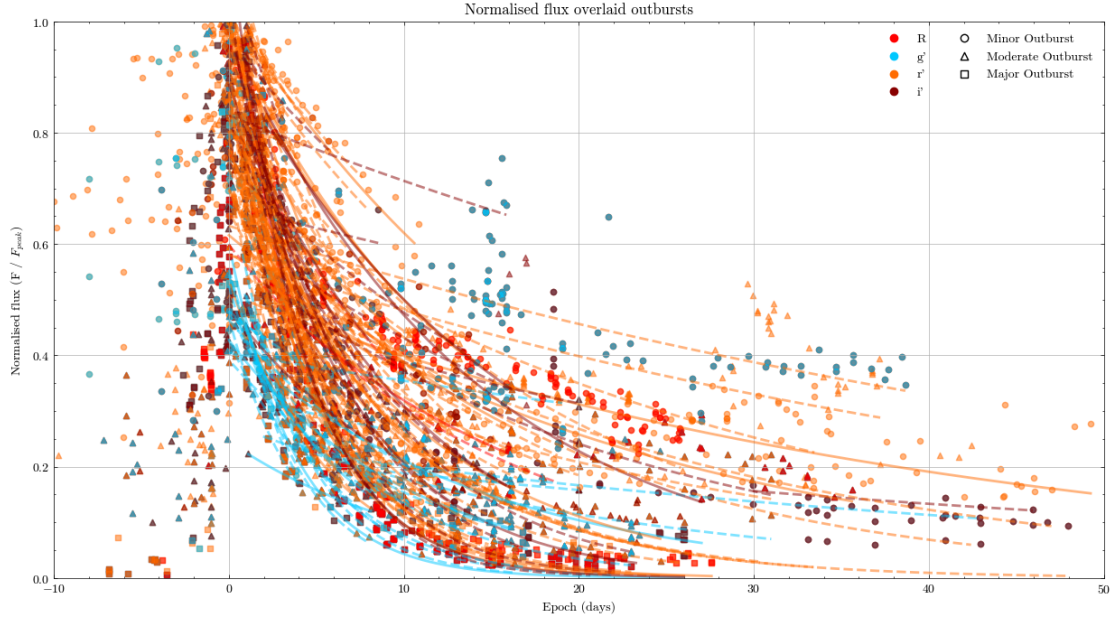


FIGURE 8.28: Exponential decay fitted to the decay period of outbursts. Outbursts are normalised such that the peak magnitude is 1.

where F is the flux and m is the magnitude. The data was fitted using SciPy's `curve.fit` function, and the expression,

$$F_{fit} = Ae^{-t/\tau} \quad (8.11)$$

where A is the amplitude of the fit (outburst intensity in this case), t is the time since an outburst occurred, and τ is the mean lifetime. The mean lifetime, τ , is the time for the function to decay to $1/e$ of its initial value. We used τ to compare different fits to assess if all outbursts decay with the same rate or if that is dependent on the outburst intensity.

The mean and minimum τ values for each filter were calculated and displayed in tab. 8.7. As mentioned, these values may be skewed by outbursts as part of a MOE. Mean values suggest that the decay for measurements made in g' filter return to quiescent brightness quickest of the filters used. This filter detects gas (eg. CN, C₂, C₃, and CO⁺ (Ivanova et al. 2017)) more than the dust ejected, therefore the gas clearly escapes the aperture quicker than the dust by ~ 4 days. Note that only a few outbursts were observed using the R filter, therefore τ values are skewed, hence the large standard error associated.

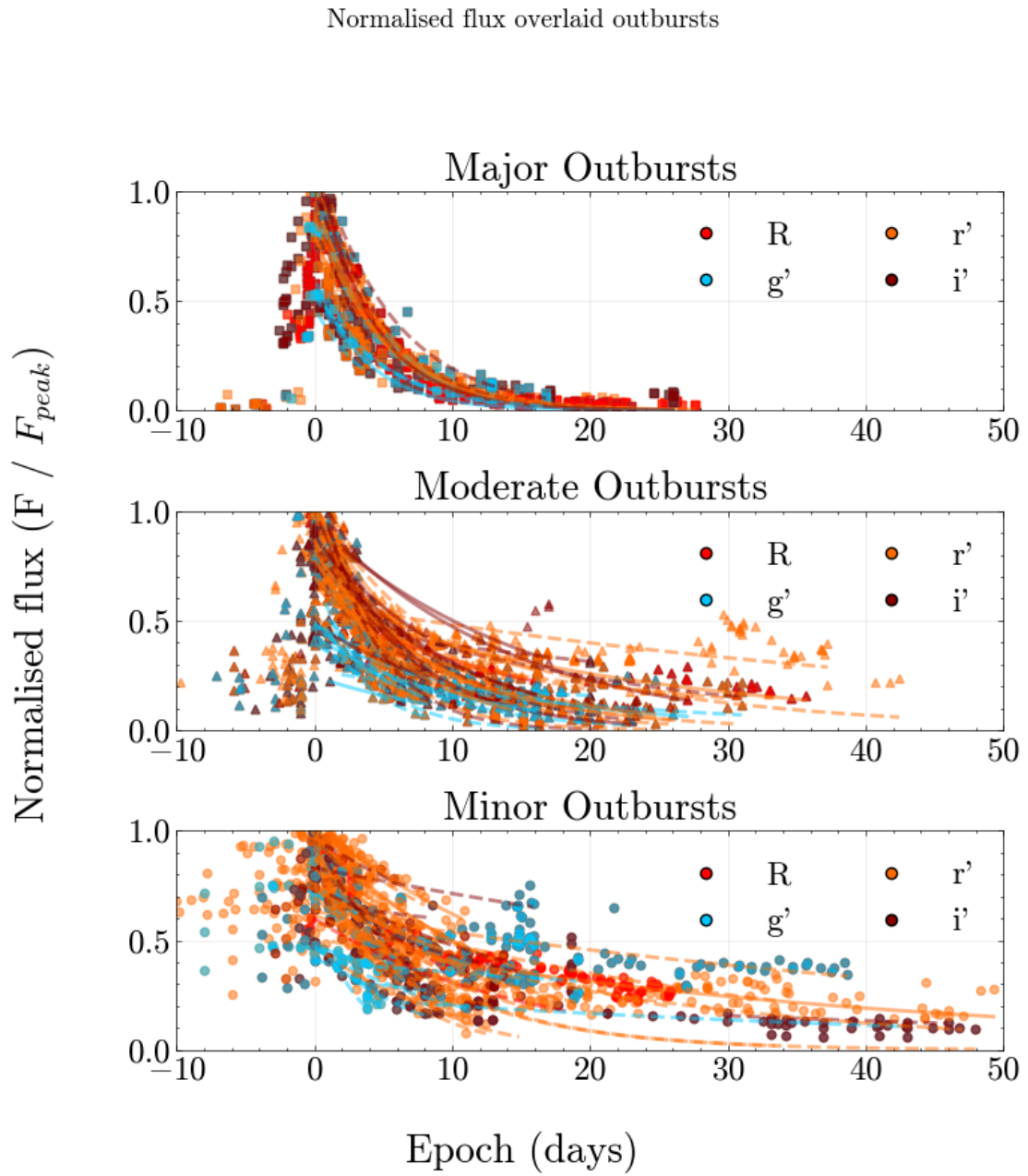


FIGURE 8.29: Exponential decay fitted to the decay period of outbursts. Outbursts are normalised such that the peak magnitude is 1. Each subplot represents an outburst type, i.e. major, moderate, or minor.

TABLE 8.7: Mean τ for multi-band observations. Changes in τ representing colour indices are listed.

Filter	Mean τ (d)	Min. τ (d)
g'	20.70 ± 6.77	3.10
r'	24.53 ± 4.74	3.10
i'	22.85 ± 6.48	3.54
R	41.95 ± 31.68	3.91
$\Delta(g' - r')$	2.67 ± 2.28	
$\Delta(r' - i')$	-0.80 ± 5.06	

Colour τ values were calculated by subtracting the τ values of a filter from that of another filter. These are also displayed in tab. 8.7. This gives the mean difference in τ for outbursts which have observations in two or more filters. Both $g' - r'$ and $r' - i'$ have large associated standard errors, suggesting a wide range of different values of τ calculated. It does, however, confirm that g' observations usually return to quiescent levels quicker than r' . Greater variability is seen in $r' - i'$ τ values, with r' and i' observations usually returning to quiescent levels at similar rates.

Fitted flux values per filter were subtracted from one another to measure the colour index change following the outburst peak. These plots resulted in straight lines, the gradients of which could be calculated. Mean values of $m_{g'-r'}$ and $m_{r'-i'}$ were found to be 0.01 ± 0.01 and 0.00 ± 0.01 , respectively. Overall, the colour index varies very little following an outburst's peak brightness. Fig. 8.30 shows this change, while most lines have very flat gradients, it is clear that some outbursts have changes in their colour index.

The τ values were plotted against outburst amplitude to assess if decay rate has a dependence on the intensity of the outburst, fig. 8.31. This plot does show that major outbursts ($\Delta m \geq 2.5$ mag) generally have shorter τ values, $\tau < 11$ d. Minor and, to a lesser extent, moderate outbursts, have a greater range of τ values. This scatter is most prominent in outburst intensities of $\Delta m < 2$ mag. Outbursts with $\Delta m < 2$ mag could eject slower moving material, meaning the

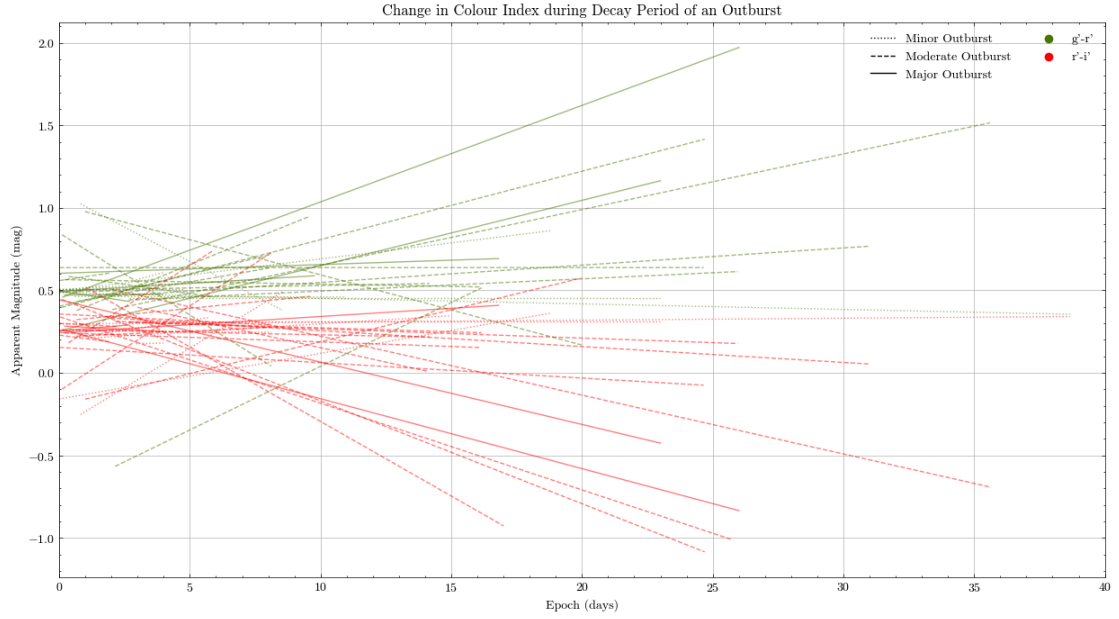
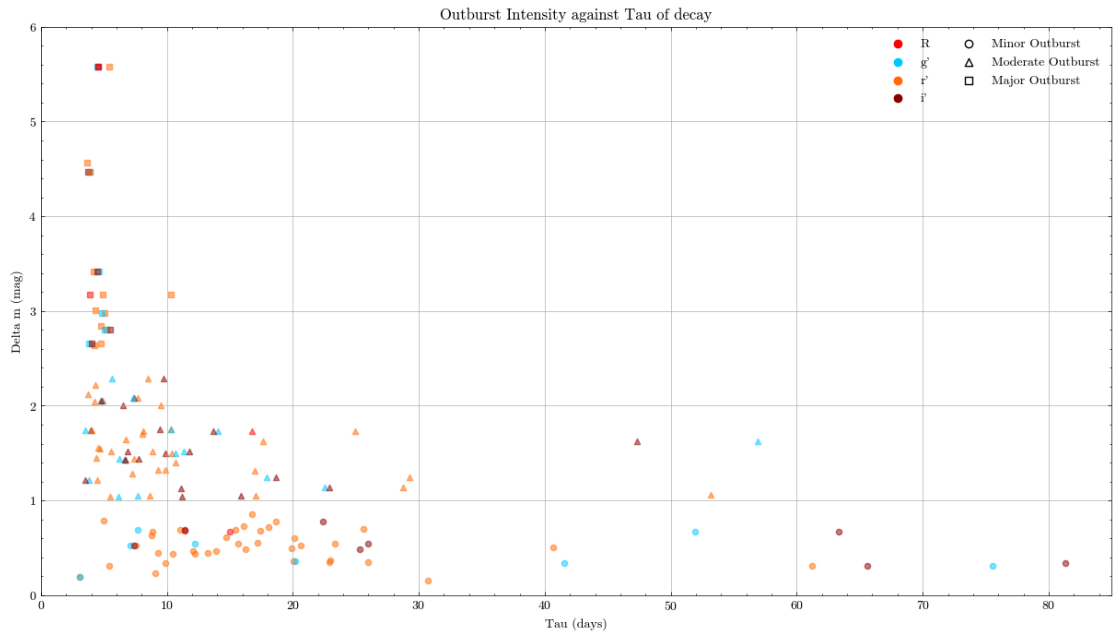
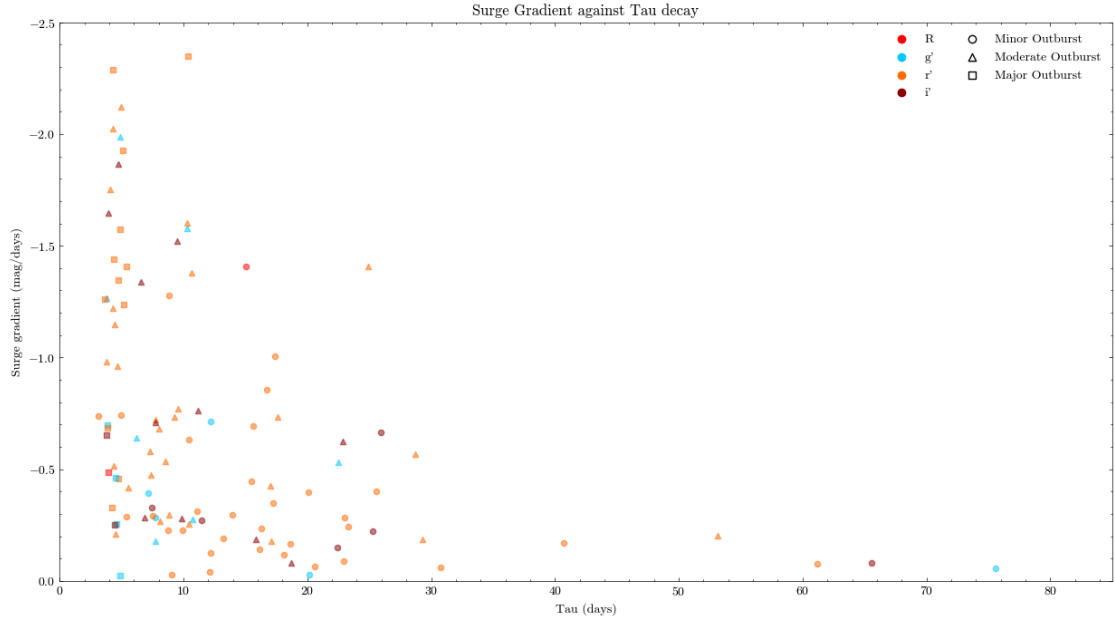


FIGURE 8.30: Change in colour index during decay period of an outburst.

FIGURE 8.31: Relation between τ and outburst intensity.

mechanism driving these outbursts may not be as intense as those which produce the major outbursts.

For outbursts where it was possible to fit the surge and decay periods, we compared the surge gradient against the decay period's τ value, fig. 8.32. No clear correlation can be seen, other than a generally shorter τ for the steepest surge gradients. There do appear to be two groups, i.e. those with surge gradients

FIGURE 8.32: Relation between surge gradient and decay τ .

greater than -1.0 mag/d and those with surge gradients less than -1.0 mag/d. This could be due to lack of outbursts observed with surge gradients around this value, or it could show that the material ejected in both groups differs. Outbursts with less steep surges have a greater range of τ values, so ejected material could take longer to reflect the greater amount of light and take longer to leave the aperture. This would be logical if this material was the heavier dust, rather than gas. Further detailed observations of the surge and decay periods are required to confirm if there are indeed two groups.

The minima magnitude and epoch are used to calculate the mean decay rate for each outburst. The mean decay rate was calculated to be $\frac{dmag}{dt} = 0.10 \pm 0.10$ mag d $^{-1}$. Decay rates for major, moderate, and minor outbursts are shown in table 8.8.

Generally, the greater the intensity of outburst, the greater the brightness decay rate, figure 8.33 shows this distribution.

A single, highly anomalous point is seen at a decay rate of ~ 0.8 , a far greater value than all other outbursts. This point is due to the decay following outburst 2020/21-D1, with a following outburst occurring less than 0.2 d after its peak

TABLE 8.8: Decay rates calculated for each outburst type.

Outburst Type	Decay Rate (mag d ⁻¹)
Major	0.18 ± 0.17
Moderate	0.11 ± 0.08
Minor	0.07 ± 0.06
Overall	0.10 ± 0.10

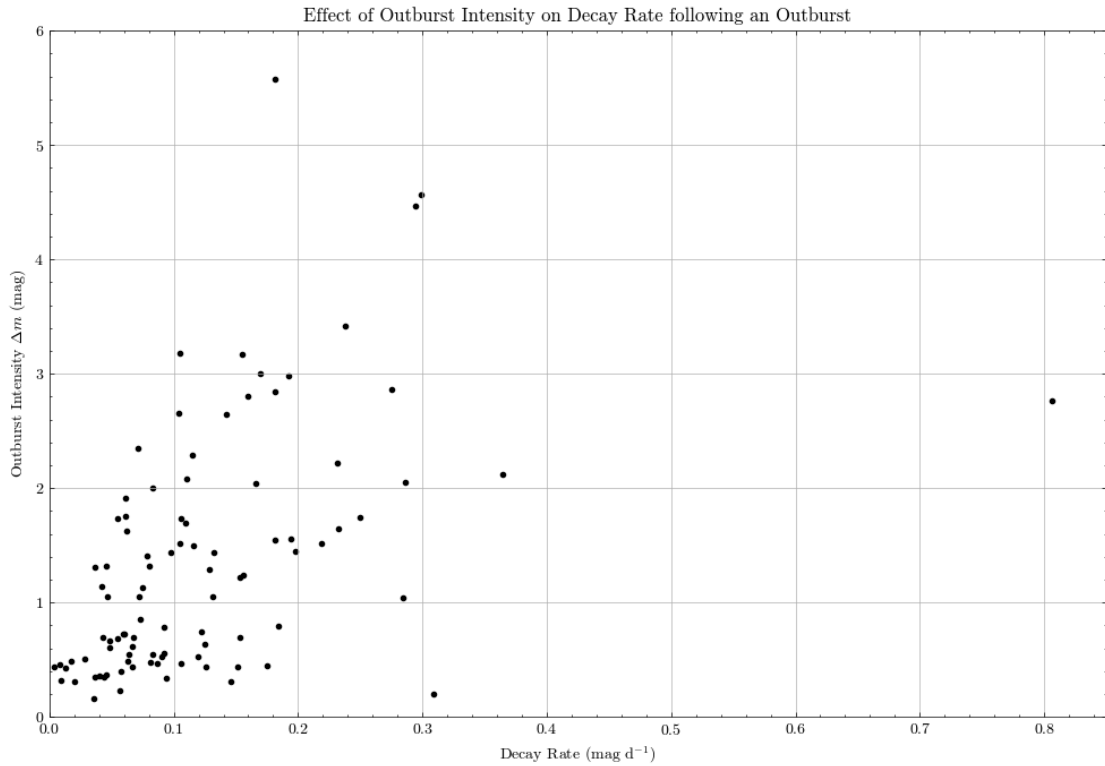


FIGURE 8.33: Distribution of decay rate for a given outburst intensity.

date. This outburst has the shortest time before the subsequent outburst occurs from all the outbursts detected in this dataset. The start of the decay period has a steeper decay rate, this is clear given that the decay rate can be fitted using an exponential function. Outbursts that occur shortly after one another will have short decay periods, thus a higher decay rate.

Figure 8.34 shows the relation between decay rate and decay time, i.e. time until next outburst. Decay rate increases as decay time decreases. It is likely that all outbursts have a greater initial decay rate, which reduces over time. This is likely due to material with insufficient speed to escape the gravitational forces

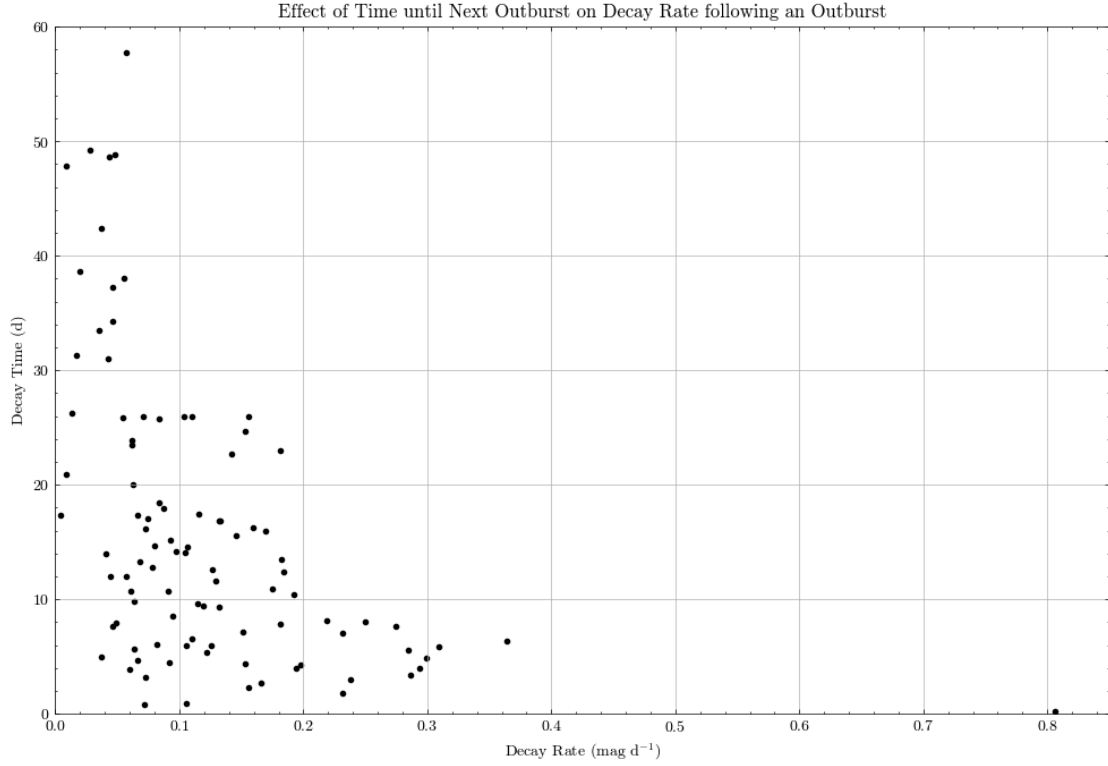


FIGURE 8.34: Relation between decay rate and decay time.

of 29P/SW1 falling back onto the nucleus shortly after peak brightness. The light reflected by this material would rapidly cease to contribute to the brightness of the object, resulting in a steep decrease in brightness. Material which has higher velocities would continue to move away from the nucleus, and would no longer contribute to the magnitude measurements once it has left the photometric aperture's field of view. This would mean the decay rate would decrease.

For outbursts with intensities $\Delta m \geq 1$ mag, the median decay rate is 0.13 ± 0.12 mag d⁻¹, similar to rates calculated by Lin (2023), who found 0.14 and 0.15 mag d⁻¹ for two outbursts (events 2018/19-F and 2020/21-B).

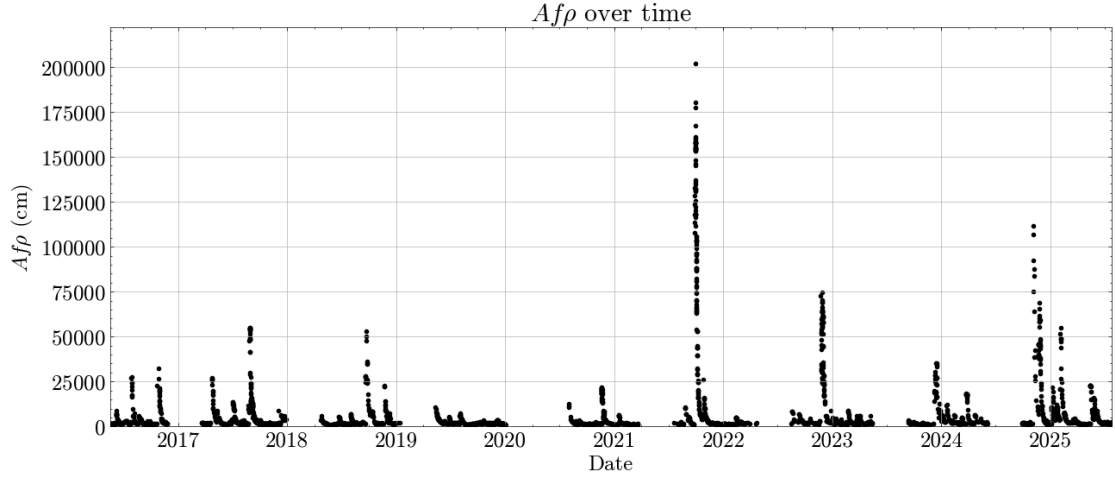


FIGURE 8.35: $Af\rho$ values for the dataset since 2016. It shows the variation in activity and intensity in different apparitions.

8.6.5 Dust Production

8.6.5.1 $Af\rho$

To assess the activity of 29P/SW1, $Af\rho$ was calculated using equation 3.17.

Figure 8.35 shows the $Af\rho$ over time for the whole dataset. This shows the variation in activity between apparitions, with a minimum occurring in 2019/20 apparition. A maximum in $Af\rho$ occurs in the 2021/22 apparition, during outburst 2021/22-C1.

Overlaid $Af\rho$ values for each outburst were plotted in figure 8.36, with $t = 0$ being the time of the outburst peak. Outbursts exhibit vastly different $Af\rho$ values. Normalising the $Af\rho$ results with respect to the peak $Af\rho$ for a given outburst is displayed in fig. 8.37. This shows that the decrease in $Af\rho$ following the peak of the outburst does not occur at the same rate regardless of outburst intensity.

With the exception of a few anomalous data points, $Af\rho$ relates to the outburst intensity at an exponential increase, see fig. 8.38.

Little correlation was seen when an outburst's peak $Af\rho$ was compared with time since the previous outburst, fig. 8.39. This suggests that larger gaps between outbursts do not build up dust beneath the nucleus to cause a greater volume ejected during the outburst.

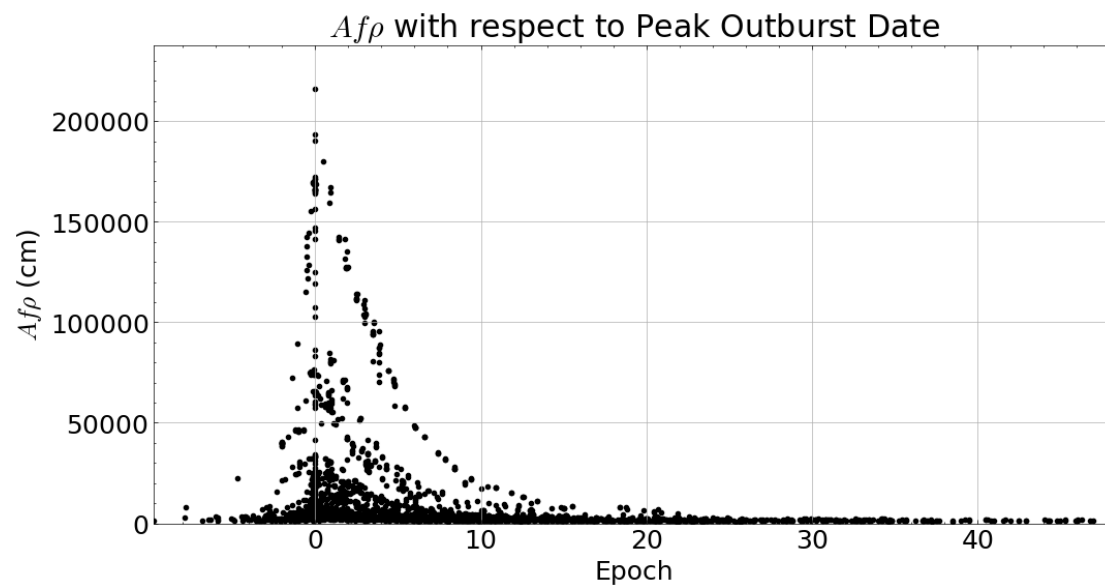


FIGURE 8.36: $Af\rho$ values with respect to an outburst's peak time.

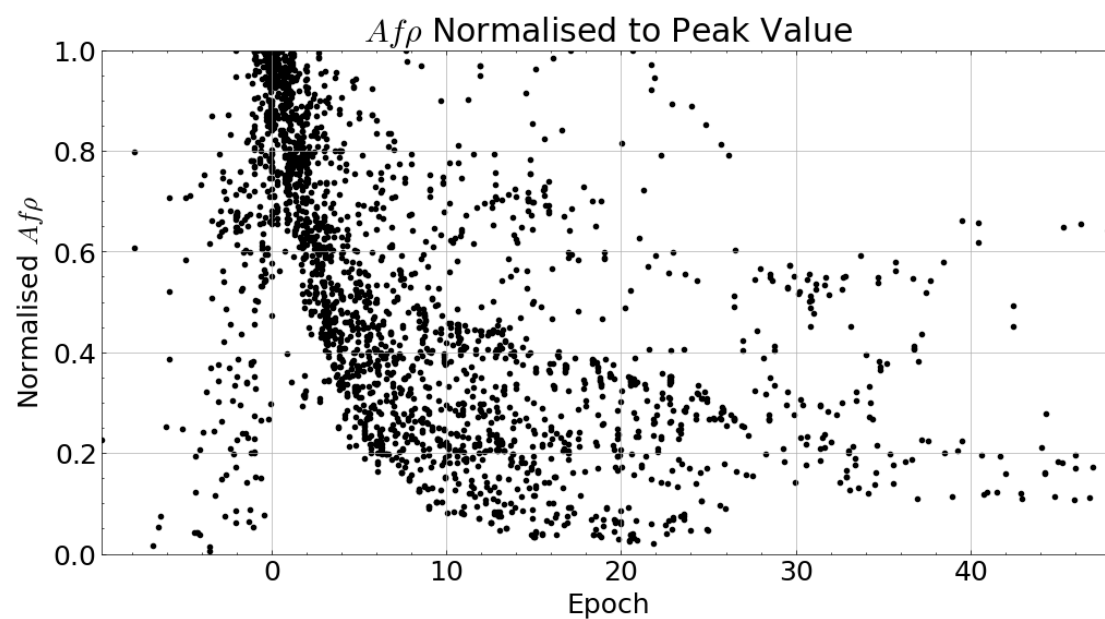


FIGURE 8.37: Normalised $Af\rho$ of outbursts overlaid with respect to the peak time.

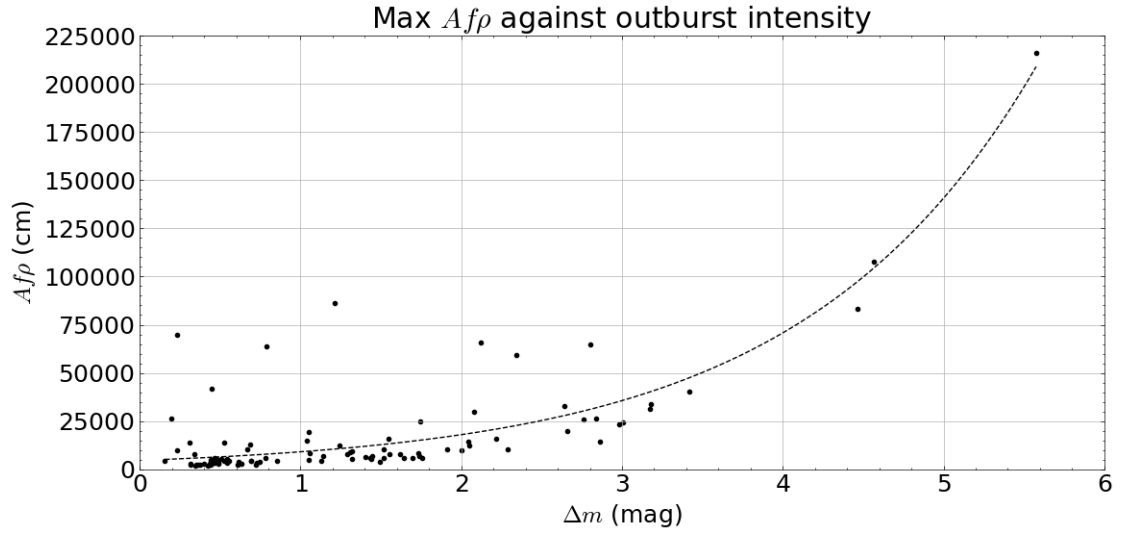


FIGURE 8.38: Outburst intensity with respect to $Af\rho$. An exponential has been fitted to the data.

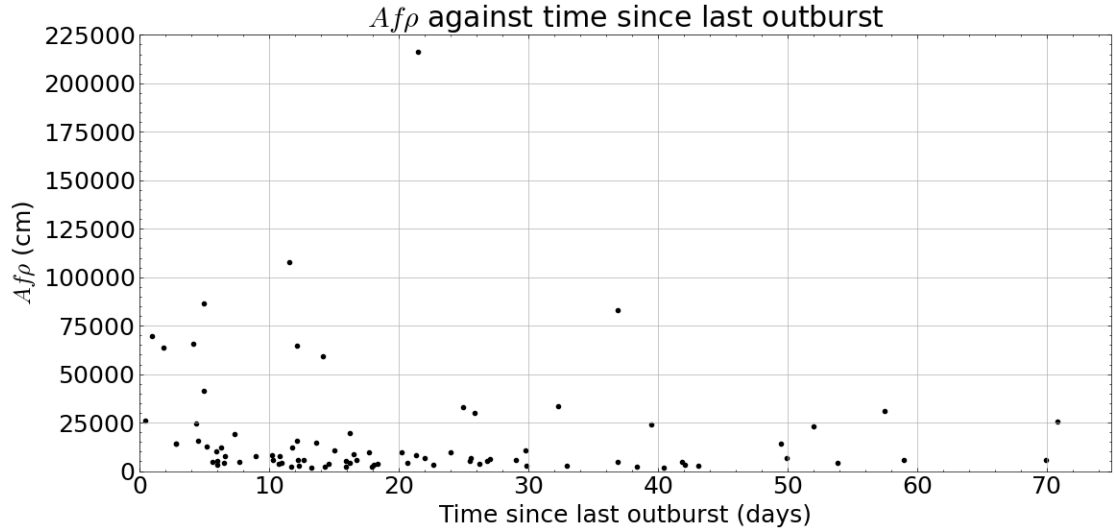


FIGURE 8.39: Maximum $Af\rho$ of an outburst with respect to time since previous outburst.

Shubina et al. (2023) found a peak $Af\rho = 17,563 \pm 982$ cm for an outburst in 2013. Lin (2023) found a peak $Af\rho = 128,740 \pm 3,624$ cm for the 2021/22-C event. This study found a max $Af\rho$ for the 2021/22-C event $Af\rho \sim 216,300$ cm. The peak brightness was detected to occur on 2021-09-28 14:00, with Cousins R-band magnitude $R = 11.00$ mag, while Lin (2023) detects the peak to occur over a day later, at 2021-09-29 20:09, with R-band magnitude $R = 11.27$ mag. We find that the $Af\rho$ at 2021-09-30 01:00, ~ 5 hours after the peak detected by Lin (2023), is $Af\rho \sim 131,500$ cm. This value is in congruent with Lin (2023),

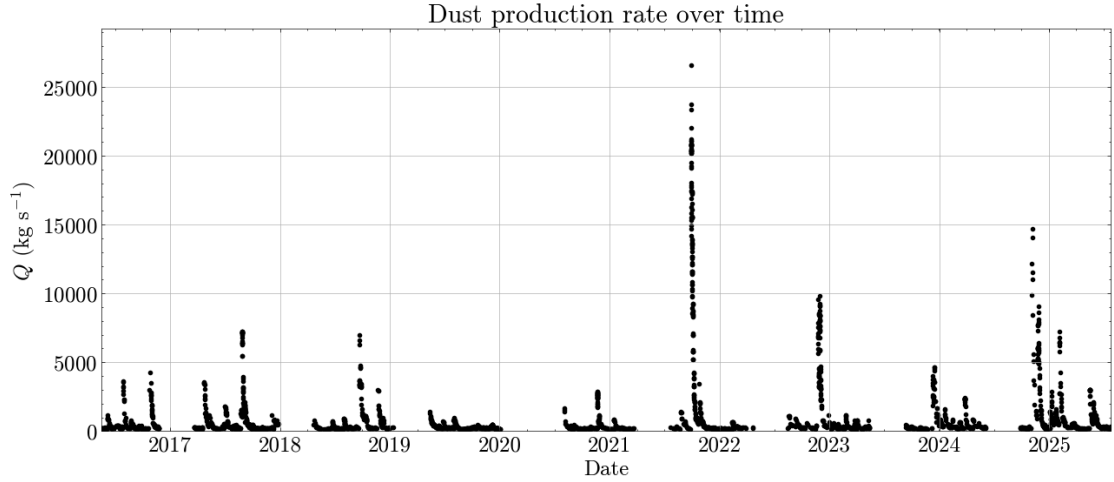


FIGURE 8.40: Dust production rate of 29P/SW1 over time.

especially considering that the aperture size of this study ($5.7''$) is larger than the one used by Lin (2023) ($5''$)

8.6.5.2 Mass Ejected

To estimate the mass ejected during an outburst, the dust production rate was first calculated using eq. 3.18, fig. 8.40. Assumptions had to be made for parameters a and ρ_d . We assumed $a = 1 \mu\text{m}$ as smaller particles do not strongly scatter light at visible wavelengths (Trigo-Rodríguez et al. 2008a). Density, ρ_d , is assumed to be 1000 kg m^{-3} , as the dust is assumed to be porous (Ivanova et al. 2011).

The maximum dust production rate calculated for this data set is $Q_{\text{dust}} \sim 28,500 \text{ kg s}^{-1}$ for the 2021/2022-C event. The outburst with the lowest dust production rate was $Q_{\text{dust}} \sim 1,780 \text{ kg s}^{-1}$.

The mass ejected was calculated using eq. 3.19.

For the 2021/22-C event, $M = 1.99 \times 10^9 \text{ kg}$ was ejected. Lin (2023) estimates the total mass lost during this event to be $M = 9.6 \times 10^9 \text{ kg}$. This discrepancy can be explained by the fact that the mass-loss calculation here assumes a fixed grain diameter of $1\mu\text{m}$, whereas Lin (2023) use a distribution of grain sizes.

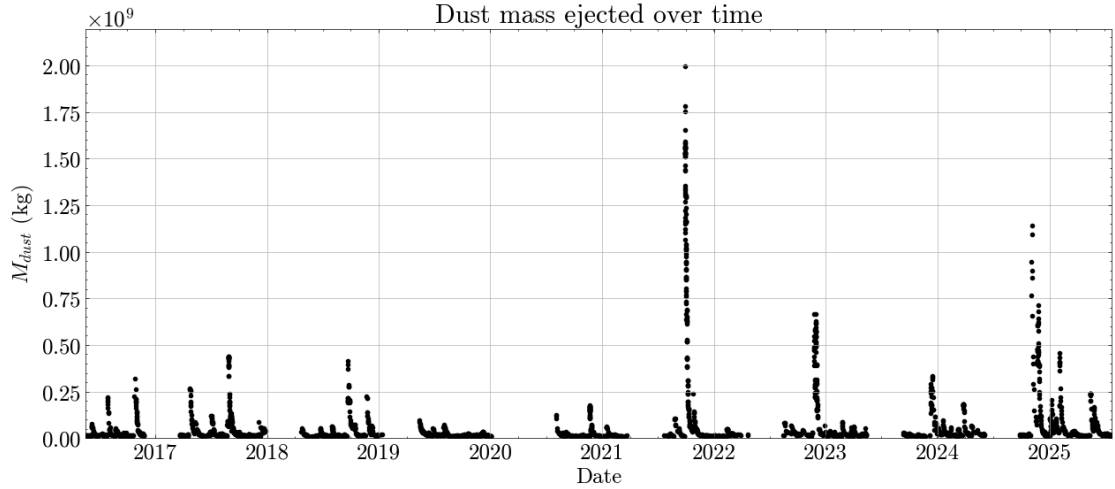


FIGURE 8.41: Mass ejected from 29P/SW1 over time.

They report that this yields a value approximately three times larger than that obtained when assuming a single grain size.

8.7 Colour Evolution

Given numerous observation runs using different filters to image the object (usually the 2.0 m Multicolour Simultaneous Camera for studying Atmospheres of Transiting exoplanets (MuSCAT) telescopes in the LCO network), colour values of $g' - r'$ and $r' - i'$ were calculated. Roughly half of the time period of the LCO dataset consists of multi-filter observations, from November 2020 onwards. Literature estimations of 29P/SW1's colour are displayed in tables 3.6 to 3.8.

8.7.1 Colour Over Apparitions

Consistent multi-filter data has been obtained since 2020 which gives weighted mean colour values of $g' - r' = 0.49$ and $r' - i' = 0.29$. The $g' - r'$ value is consistent with solar colour of $g' - r' = 0.45 \pm 0.02$, while the $r' - i'$ deviates more from the solar colour $r' - i' = 0.12 \pm 0.01$ (Holmberg et al. 2006).

On a long-term scale, a cubic polynomial was fitted which approximates the general trend in the change of colour over the 5 years of data available. Both

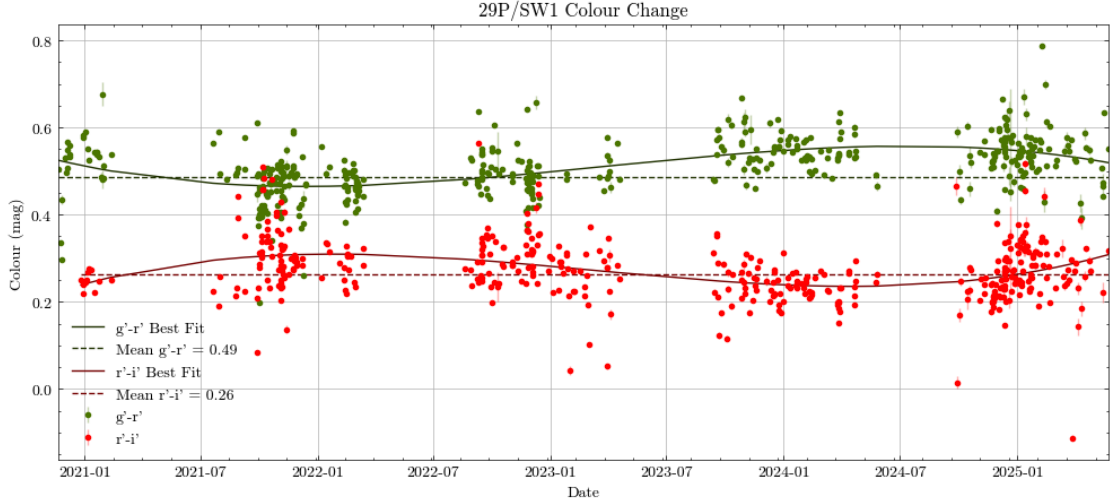


FIGURE 8.42: SDSS colour indices variation over time. Mean values and a fitted sine curve have been overlaid on the data.

colours calculated follow a roughly similar yet inverse pattern in the best-fit curve. This data against time can be seen in figure 8.42. Figure 8.42 shows the almost sinusoidal polynomial fit to each dataset. If treated as a sine wave, the wavelength would be roughly $\lambda_{g'-r'} \approx 1880 \text{ days} \approx 5.2 \text{ years}$ and $\lambda_{r'-i'} \approx 1630 \text{ days} \approx 4.5 \text{ years}$, and amplitude $A_{g'-r'} = 0.05 \text{ mag}$ and $A_{r'-i'} = 0.04 \text{ mag}$. Given the large periods without data between apparitions, and that the data only spans 5 years in total, this trend is purely indicative of how the colour may change. Further multi-filter, long term observations will be required to confirm if this trend continues or is a coincidence. The $R(1, 1, 0)$ magnitude was used to calculate the colour to mitigate any variations that may occur due to the Centaur's orbit.

A weighted mean value was calculated to estimate the average $g' - r'$ and $r' - i'$ colours over the 4+ years' worth of multi-filter data available in the LCO archive. While the colours do vary from apparition to apparition, it is useful to calculate mean colour values as to begin to compare with literature values which generally use small time frames. $g' - r' = 0.49 \text{ mag}$ and $r' - i' = 0.26 \text{ mag}$. The weighted mean colour per apparition has also been calculated, see table 8.9.

Using the methodology described in appendix L, the colour index in the Johnson-Cousins filter set was calculated to compare values in this study with those in

TABLE 8.9: Mean colour indices per apparition.

Apparition	$g' - r'$	$r' - i'$
2020/21	0.52 ± 0.01	0.25 ± 0.01
2021/22	0.46 ± 0.01	0.30 ± 0.01
2022/23	0.49 ± 0.01	0.29 ± 0.01
2023/24	0.55 ± 0.01	0.24 ± 0.01
2024/25	0.54 ± 0.01	0.27 ± 0.01
Mean	0.51 ± 0.01	0.27 ± 0.01

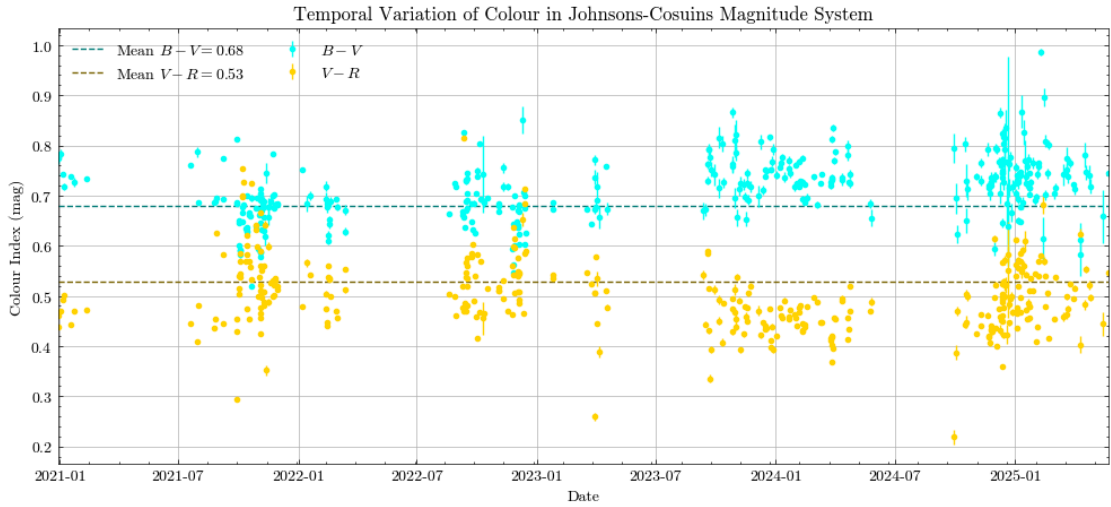


FIGURE 8.43: Johnson-Cousins colour indices variation over time. Mean values and a fitted sine curve have been overlaid on the data.

the literature. Average $B - V$ and $V - R$ values were found to be 0.73 ± 0.01 mag and 0.53 ± 0.02 mag, respectively. These values are very similar to the mean value calculated from literature colour index values, shown in tables 3.6 and 3.8.

8.7.2 Colour Slope

Variations in the colour with respect to the observed wavelength can be estimated using its colour slope, S' (A'Hearn et al. 1984). Using this value can help investigate the broad composition of the coma, with larger S' corresponding to a redder, dust-heavy environment, while a smaller S' corresponds to a bluer, icier environment. This value is calculated using an adapted equation by Voitko et al.

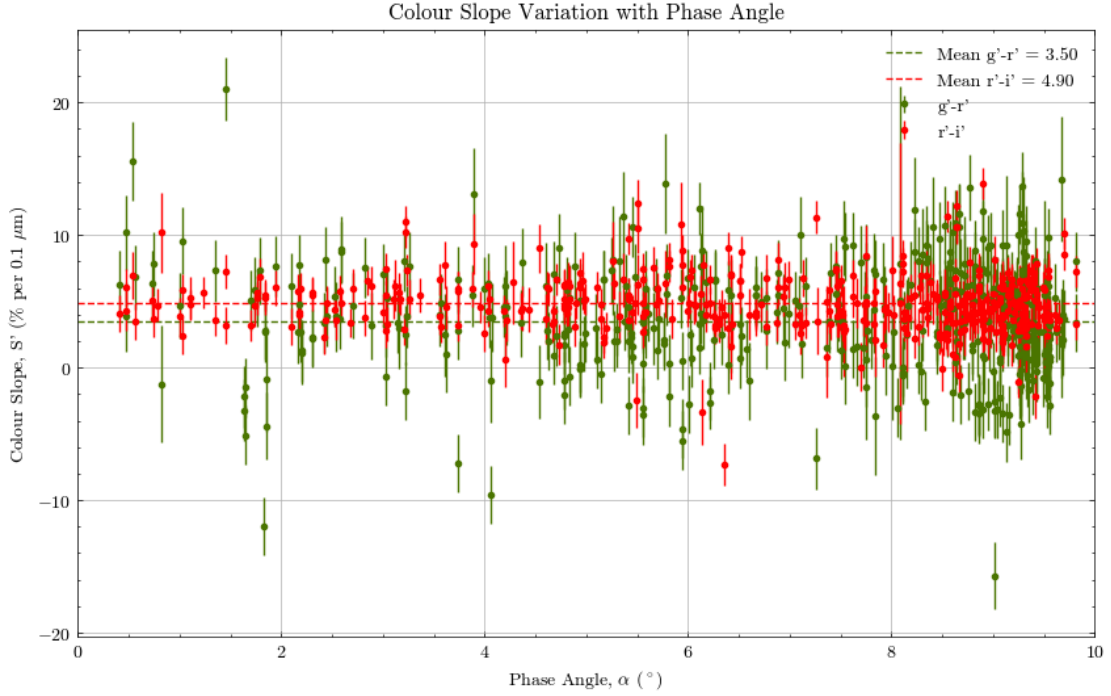


FIGURE 8.44: Colour slope with respect to phase angle.

2022 initially proposed by A’Hearn et al. 1984.

$$S' = \frac{10^{0.4\Delta m} - 1}{10^{0.4\Delta m} + 1} \times \frac{20}{\lambda_2 - \lambda_1} \quad (8.12)$$

where Δm is the ‘true colour’, i.e. the apparent colour minus the solar colour, and λ_1 and λ_2 are the effective wavelengths of the filters used to calculate the colour, i.e. $colour_1 - colour_2$. Solar colours in SDSS filters were obtained from Holmberg et al. 2006, $g' - r' = 0.45 \pm 0.02$ mag and $r' - i' = 0.12 \pm 0.01$ mag. Effective wavelengths for SDSS filters were obtained from SDSS n.d., $g' = 477.0$ nm, $r' = 623.1$ nm, and $i' = 762.5$ nm.

The colour slope was calculated for each colour value calculated and this was then plotted against the phase angle of the Centaur, figure 8.44. A weighted mean was calculated for each colour, and found to be $g' - r' = 3.67 \text{ } \%/ \mu\text{m}$ and $r' - i' = 4.90 \text{ } \%/ \mu\text{m}$.

We assessed the colour slope with respect to the time since the outburst peak, fig. 8.45. Large scatter and large errors make analysis of this data difficult. There appears to be an increase in $r' - i'$ and a decrease in $g' - i'$ following an outburst’s

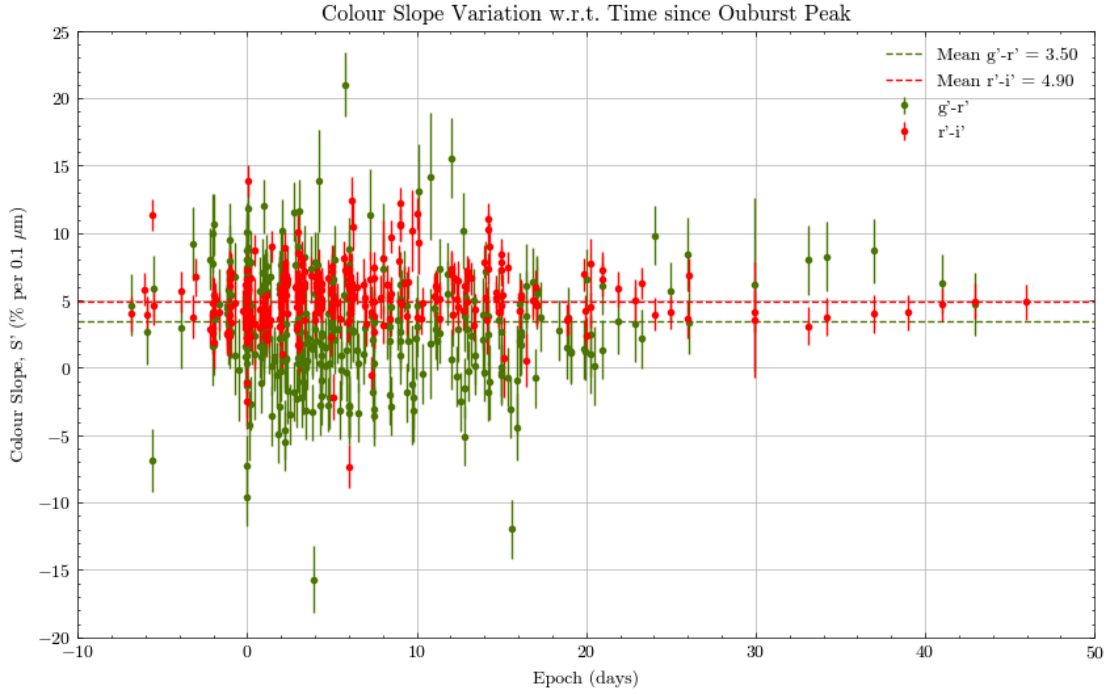


FIGURE 8.45: Colour slope with respect to time since outburst peak.

peak, returning to quiescent levels after ~ 10 d. It is not currently possible to quantify this, and doing so would require further multi-filter observations to confirm. If this colour change does occur in both indices, it would suggest that the near-nucleus environment would become more dust-rich, before returning to its quiescent level.

8.7.3 Colour-Colour Diagram

A colour-colour diagram was plotted to observe if any variation in colour occurs during outbursts, i.e. when the r' magnitude decreases suddenly. Points in figure 8.46 were coloured based on their r' magnitude, the brighter the object, the darker the colour on the diagram, and vice versa.

Values mostly cluster centrally on the diagram between $g' - r' \sim 0.45 - 0.62$ mag and $r' - i' \sim 0.18 - 0.35$ mag, with the brightest data points tending towards the lower-left edge of this cluster. This suggests that during an outburst both colours decrease, causing a bluer colour.

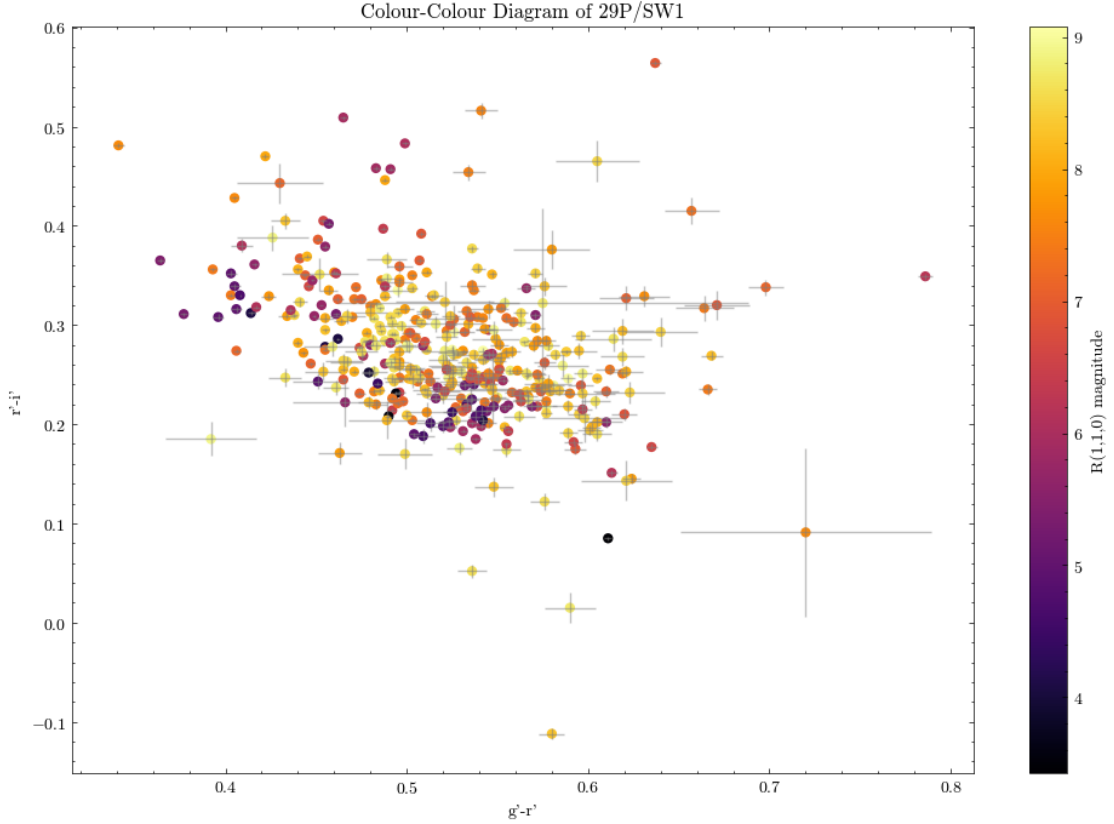


FIGURE 8.46: Colour-colour diagram of 29P/SW1. Marker colours varies with reduced magnitude intensity, darker colours represent brighter datum.

This appears counter-intuitive to what would be expected given that dust is expected to be released during an outburst and would appear redder due to the scattering of the sunlight by the small particles. This is only the case for the brightest outbursts, and therefore the number of data points available is very limited. The most intense outbursts therefore may be dominated by gas. Data points with r' $R(1,1,0)$ magnitudes between $\sim 9 - 7.5$ mag, i.e. during quiescence or moderate outbursts, cover the whole cluster with no discernable or clear trend.

8.7.4 Outburst Colour Variation

Colour index values were overlaid at epoch $t = 0$ for the peak of the outburst, fig. 8.47. This shows how the $g' - r'$ and $r' - i'$ indices vary throughout the

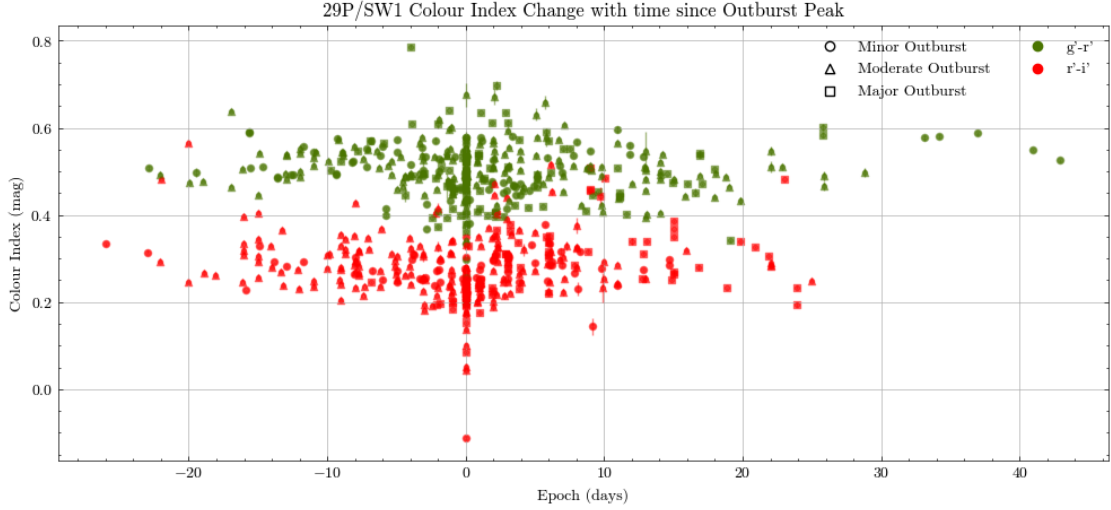


FIGURE 8.47: Overlaid outburst variations in colour index with respect to time since the outburst peak.

outburst. Surge and decay periods appear somewhat constant over time, although greater spread of values appear around $t = 0$. Figure 8.48 shows the rolling mean for each day of the epoch, as to measure the trend around the outburst's peak point. A decrease in $g' - r'$ and $r' - i'$ indices is seen, with a more significant decrease in $r' - i'$. This suggests that more dust is ejected around this period, reflecting the longer wavelength light more.

Some outbursts have a far smaller $r' - i'$ index at the outburst's peak, these outbursts are not exclusively within a outburst type (e.g. minor, moderate, major). These outbursts could have higher proportions of dust making up the ejecta, independent of outburst intensity.

8.8 Short-Term Analysis

Outburst 2023/24-B began at 2024-03-08 20:43, with peak at 2024-03-09 00:45, with intensity $\Delta m = 1.43$ mag. This outburst was detected and initially observed at the Skalnaté Pleso Observatory during an Europlanet funded observing trip. Following detection of the outburst, LCO images were requested and other observers of 29P/SW1 were notified of this event.

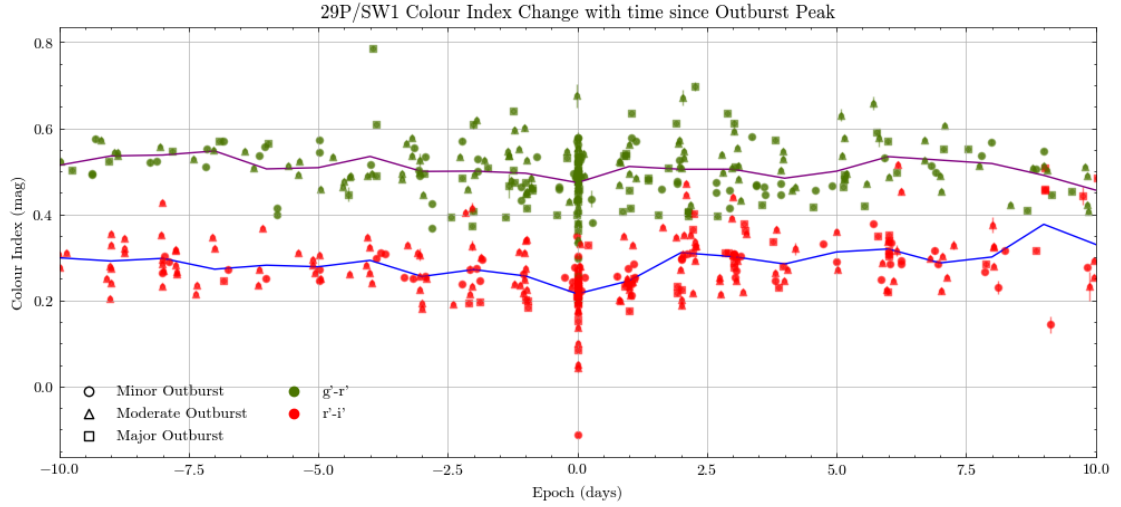


FIGURE 8.48: Overlaid outburst variations in colour index with respect to time since the outburst peak. Rolling average for each day has been plotted, and limited to ± 10 d from outburst peak.

This detailed observations of the initial period of the outburst allows this event to be treated as a short-term case-study.

TABLE 8.10: Summary of outbursts during the 2023/24-B event. Start and peak dates are listed, along with change in magnitude of outburst, and surge and decay rates for each outburst.

	Start Date	Peak Date	Δm (mag)	Surge Rate (mag d ⁻¹)	Decay Rate (mag d ⁻¹)	# Obs.
B	2024-03-08	2024-03-09	1.43	-8.51	0.10	20

8.8.1 Image Processing

This outburst contains the only data not from the [LCO](#) network, thus did not have the BANZAI pipeline post-processing. Bias, dark fields, and flat fields were taken during observing. We call the images of the desired object the ‘lights’.

The Siril programme was used to calibrate the raw images.

Each [CCD](#) has biases in the field as each sensor has its own read-out noise, varying the signal from pixel to pixel. The bias image is a stack of short exposures taken with the telescope’s lens cap on at the start of an observing run.

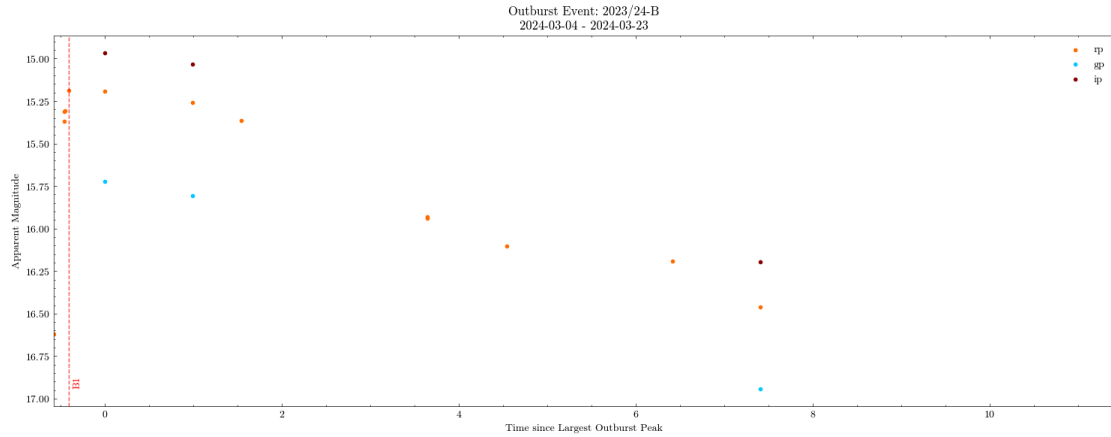


FIGURE 8.49: Lightcurve of event 2023/24-B. Peak of outburst is marked with a dashed red line.

This shows the inherent biases in the [CCD](#), which can be subtracted from the lights.

Dark fields are taken, again, with the lens cap on or on an empty part of the sky, but exposure time equals those for the lights. This demonstrates the effect that the temperature of the camera has over the duration of the exposure, the thermal noise produced for this field can be subtracted from the lights.

Finally, the flat field images are taken. These are obtained by imaging a white screen, highlighting variation in the [CCD](#) when observing an illuminated source. Additionally, the flats show any dust that lie on the mirror. Flats were taken for each filter used. The flat can be divided from the lights with bias and dark fields subtracted.

Master bias, darks, and flats were created using Siril and built-in scripts. These were subtracted from the lights to form the processed images. It was then possible to process these images using the pipeline.

8.8.2 Outburst Analysis

Lightcurve of this event is provided in [fig. 8.49](#) in different filters.

The magnitude of 29P/SW1 at varying aperture sizes displays how the coma distribution varies over time around an outburst, fig. 8.50. The red data is the start of the outburst (2024-03-08 20:43), less than 3 hours later, the near-nucleus magnitude decreases by > 2 mag (2024-03-08 23:34). We can see that after an hour, the magnitude of the object within 6,200 km begins to increase, while the magnitude continues to decrease at distances of 6,200 to 62,000 km. Material ejected during the outburst has moved beyond 6,200 km in ~ 4 hr, suggesting an ejecta velocity of $v_{ejecta} \approx 0.4 \text{ km s}^{-1}$ almost 4 times the outburst velocity calculated by Schambeau et al. (2017) and Lin (2023), but similar to velocities of CO measured by Womack et al. (2017) for 29P/SW1.

Days following the outburst, we observed the plateau of the radial profile to assess the velocity of dust ejected during this outburst. On 2024-03-13 01:54, the plateau occurs at $\sim 55,000$ km, while almost a day later at 2024-03-13 23:29, the plateau occurs at $\sim 60,000$ km. This gives a velocity of $v_{ejecta} < 0.1 \text{ km s}^{-1}$.

The radial profile returns to similar values as the start after ~ 8 d. Coma brightness is still brighter within $\sim 67,000$ km, yet similar brightness at greater distances.

The surface brightness of the object was calculated and plotted against aperture size. A ‘knee’ can be seen in this data, with the inner part accelerating particles within this radius (Jewitt and Meech 1987). Gradient of $m = -1$ represents symmetric steady-state coma expansion, any smaller gradient would represent that the particles are accelerating. Figure 8.51 displays the surface brightness for this outburst, diagonal black lines on the bottom left of the plot display $m = -1$ and -1.5 gradients. Nearer to the nucleus, the gradient for most profiles are $m > -1$, only around peak time of the outburst does the profile steepen $m < -1$. After the ‘knee’, the slope steepens, approaching $m = -1.5$.

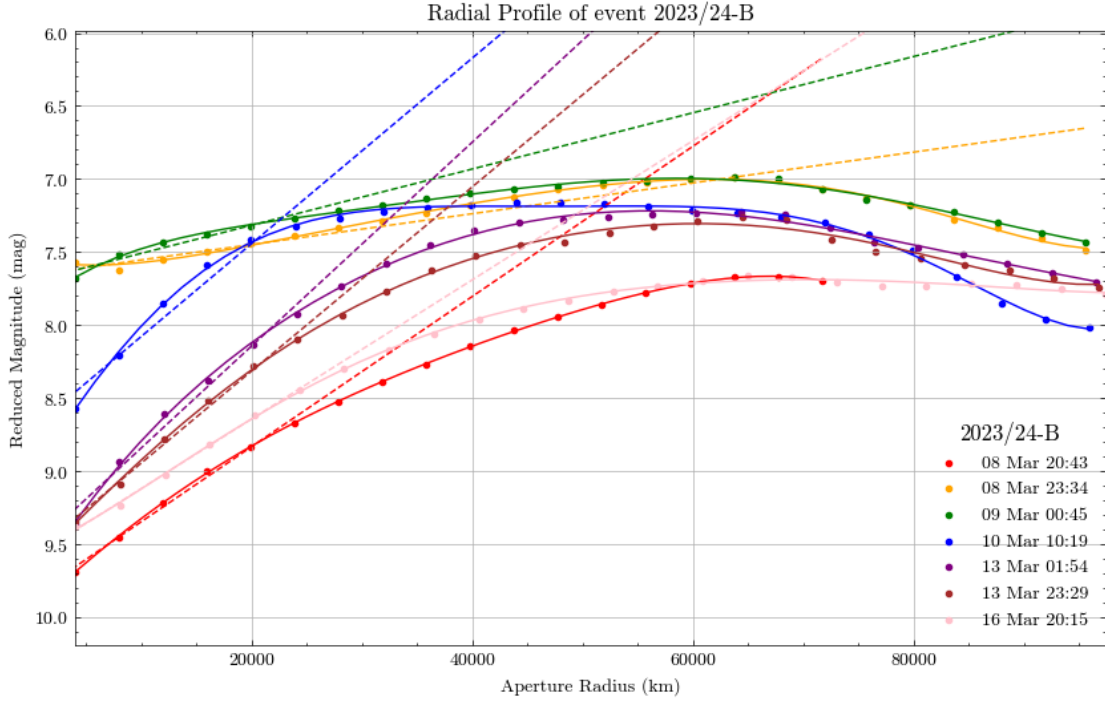


FIGURE 8.50: Radial profile of outburst 2023/24-B with outburst peak on 2024-03-09. The outburst had intensity of $\Delta m = 1.43$ mag. Lines in different colours represent radial profiles at different times. Straight, dashed lines fit the data within 25,000 km of the nucleus.

8.9 Summary

12,083 images were obtained from the [LCO](#) network and Skalnaté Pleso Observatory, in SDSS filters g' , r' , i' , and Cousins R. Data was obtained between May 2016 until July 2025, spanning 9 apparitions. Quality analysis was conducted to filter out images with poor [SNR](#) or issues during observing.

[29P/SW1](#) was found to be in an outbursting state for $> 80\%$ of the period observed. 98 outbursts of $\Delta m > 0.2$ mag were detected in this dataset. 14.6 ± 1.0 outbursts of $\Delta m > 0.2$ mag occur per year, with a mean intensity of $\Delta m = 1.3 \pm 0.1$ mag. A mean of 7.9 outbursts of $\Delta m > 1$ mag per year was found, similar to the number found by Trigo-Rodríguez et al. (2010).

Outburst intensities can be categorised into 3 broad groups, minor ($\Delta m < 1.0$ mag), moderate ($1.0 \leq \Delta m < 2.5$ mag), and major ($\Delta m \geq 2.5$ mag).

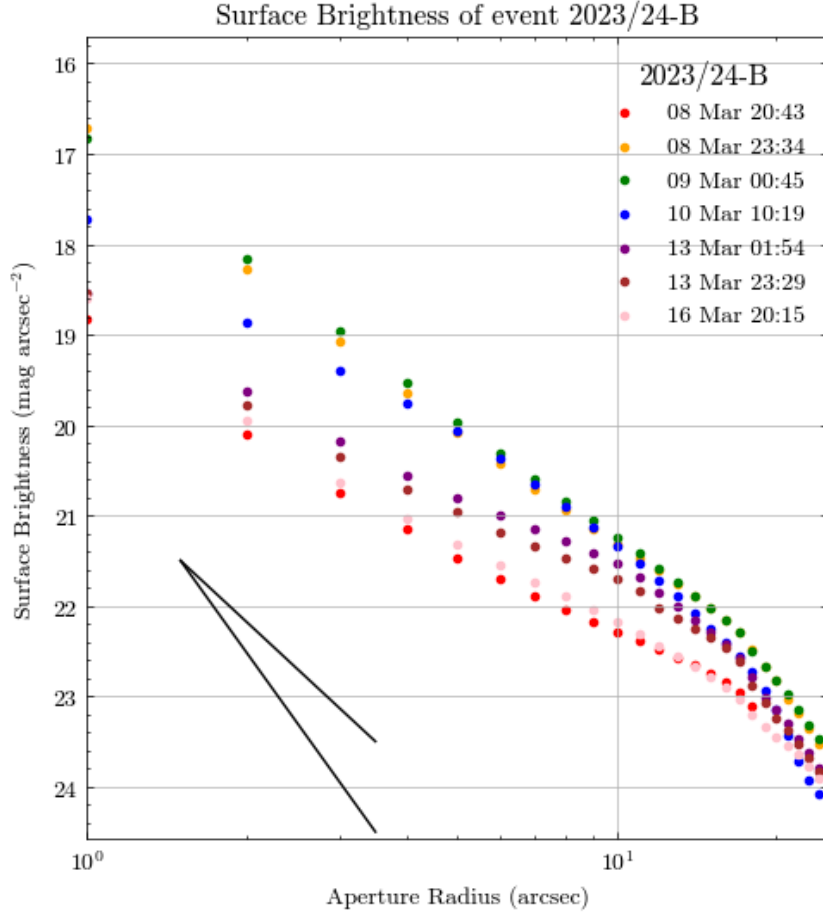


FIGURE 8.51: Surface brightness profile over time. Diagonal black lines on the bottom left display $m = -1$ and -1.5 gradients.

Few outbursts occur at the threshold intensities, suggesting that multiple mechanisms could be triggering outbursts to occur. 46% of outbursts are minor, 38% are moderate, and 14% are major.

During an outburst's surge period, the object brightens at a rate of $< -0.89 \pm 0.63 \text{ mag d}^{-1}$ for measurements made in r' filter. This value is dependent on the observing cadence, therefore stands as an upper limit for the actual average surge rate. From analysing the decay rates of the observed outbursts, gas appears to expand further than the $5.7''$ aperture after $\sim 4 \text{ d}$. A mean decay rate of $0.10 \pm 0.10 \text{ mag d}^{-1}$ was calculated, with major outbursts having a larger decay rate compared with moderate and minor outbursts.

A maximum $Af\rho$ was calculated to be 216,300 cm for the 2021/22-C outburst event. This corresponds to a dust production rate of $Q_{\text{dust}} \sim 28,500 \text{ kg m}^{-3}$,

with $M_{dust} \sim 1.39 \times 10^{12}$ kg ejected during this event. Outbursts with $\Delta m < 2$ mag appear to have slower moving material ejected.

Intensive observations of outburst 2023/24-B allowed detailed radial profile and surface brightness analysis. During this event, gas was ejected at a velocity $v_{gas} \sim 0.4 \text{ km s}^{-1}$, with dust ejected at a velocity $v_{dust} < 0.1 \text{ km s}^{-1}$.

Variations in colour during an outburst were not well defined. Generally, the colour index remained constant throughout the whole outburst, with minor reddening observed around the peak of the outburst.

Using images obtained during quiescent periods, the nucleus size was estimated to be $37.3 \pm 11 \text{ km}$, by calculating the zero-radius magnitude of radial profile data. This value is similar to those estimated by Schambeau et al. (2015), Schambeau et al. (2021), and Bockelée-Morvan et al. (2022).

Chapter 9

Discussion

This chapter interprets the scientific and pedagogical findings of the project, discussing their implications, limitations, and relationship to existing literature.

Section 9.1 evaluates the photometric results of Centaur [29P/SW1](#); Section 9.2 discusses the educational outcomes of the Comet Chasers’ programme. Such detailed, long-term analysis of [29P/SW1](#) would not have been possible without the hard work of Comet Chasers’ schools obtaining images of this fascinating object.

9.1 Cometary Astronomy

Three distinct outburst intensity groups were identified in the data: *major* ($\Delta m \geq 2.5$ mag), *moderate* ($1.0 \leq \Delta m < 2.5$ mag), and *minor* ($\Delta m < 1.0$ mag), with few observed events occurring near the group boundaries. Minor outbursts have previously been reported by Miles ([2016b](#)), with intensities of $\Delta m \sim 0.7$ mag, although no explicit classification scheme was proposed in that study. The presence of relatively well-defined intensity groupings suggests that outbursts of different magnitudes may arise from distinct physical mechanisms.

This interpretation is consistent with the proposal by Miles ([2024a](#)) that outbursts may be driven by cryovolcanic processes. However, the identification of

distinct intensity classes alone does not demonstrate that cryovolcanism uniquely accounts for all observed events, nor does it exclude crystallisation of [AWI](#) as a triggering mechanism.

The results presented here suggest that [AWI](#) crystallisation could plausibly account for at least the minor and moderate outbursts. The calculated temperature contrast between the [sub-solar point](#) and the average surface temperature is sufficient to induce the transition from [AWI](#) to [CWI](#). This agrees with previous studies that the nucleus of [29P/SW1](#) is large (Bockelée-Morvan et al. [2022](#); Kokhirova et al. [2020](#); Schambeau et al. [2021](#)), therefore a substantial reservoir of unprocessed [AWI](#) could exist, and maintain the high frequency of minor outbursts detected.

For [cryomagma](#) to form, sufficient pressure within cavities beneath the crust is required for liquid to exist. Gas release associated with [AWI](#) crystallisation could contribute to this pressure increase if [volatiles](#) are sufficiently trapped, while the heat released during crystallisation may cause melting of methane ice and the [sublimation](#) of other common [volatiles](#).

On average, 15.3 outbursts are expected to occur each year, accounting for outbursts with $\Delta m > 0.2$ mag. This rate is comparable to those found by Trigo-Rodríguez et al. ([2010](#)) (counting only outbursts with $\Delta m > 1.0$ mag), suggesting that the frequency of moderate and major outbursts has remained consistent for the last ~ 20 years. The number of outbursts per apparition has varied in the 9 apparitions analysed. No major outbursts were detected during the 2019/20 apparition, whereas in subsequent apparitions there was an increase in the total number of outbursts.

This supports the hypothesis by Miles ([2016a](#)) that there is seasonality, which allowed a rotational period to be estimated via the outbursting periodicity. [29P/SW1](#) is in an active state for over 80% of the time, suggesting that a persistent coma remains around the nucleus, consistent with Bockelée-Morvan et al. ([2022](#)), Lin ([2023](#)), and Wierzchos and Womack ([2020](#)).

Continuing observations for future apparitions are necessary to discern if the reduced number of major outbursts is due to its orbital position, rotational inclination angle, or anomalous activity.

Average colour indices for the whole dataset were found to be $g' - r' = 0.49$ and $r' - i' = 0.29$. The $g' - r'$ index is similar to the respective solar colour index, while the $r' - i'$ index is more than twice the solar value (Holmberg et al. 2006). This implies that the Centaur's coma is dusty, reflecting light with longer wavelengths more readily.

Some colour variation is seen during the surge period of an outburst, with the $g' - r'$ index decreasing slightly, while $r' - i'$ index remains constant. This corresponds to a steeper surge rate for g' observations compared to r' , suggesting that the colour becomes bluer (as colour index decreases) during this period, consistent with gas dominating the aperture during the early period of the outburst.

The variation in colour index is most pronounced during higher-intensity outbursts, likely reflecting the increased release of material and a larger relative contribution from gas-rich components. When plotting the $g' - r'$ index against the $r' - i'$ index, values clustered between $g' - r' = 0.45 - 0.62$ and $r' - i' = 0.18 - 0.35$. The brightest data points had the brightest measurements suggesting that the outbursts peaks are bluer.

By fitting exponential decay functions to the post-outburst light curves, the characteristic decay timescale τ – defined as the time required for the brightness to decrease by a factor of e – was determined. Mean τ values for the SDSS filters g' , r' , and i' were found to be 20.7, 24.5, and 22.9 d, respectively.

The shorter τ measured in the g' band indicates that the effective residence time of gas-dominated material within the photometric aperture is shorter than that of dust, in agreement with Wierzechos and Womack (2020). Across all three

filters, a minimum observed decay timescale of $\tau_{\min} = 3.1$ d was found, representing the fastest brightness decay detected. This is consistent with Trigo-Rodríguez et al. (2008b), who reported that 29P/SW1's brightness typically returns to its initial state within 3–4 d, comparable to the shortest τ values measured here.

Outbursts with intensities $\Delta m < 2$ mag exhibit a wider range of τ values, suggesting that ejected material remains within the aperture for longer periods. This behaviour is consistent with a larger relative contribution from dust-rich ejecta, which are expected to expand at lower velocities than gas. A mean decay rate of 0.10 ± 0.10 mag d^{−1} was found, similar to the rate derived by Lin (2023). When only moderate and major outbursts are considered, this rate increases to 0.13 ± 0.12 mag d^{−1}.

Gas and dust ejection velocities for a major outburst were estimated to be $v_{\text{gas}} \sim 0.4$ km s^{−1} and $v_{\text{dust}} < 0.1$ km s^{−1}, respectively. Womack et al. (2017) reported comparable expansion velocities for CO gas, while similar dust velocities have been inferred by Schambeau et al. (2017) and Lin (2023).

A maximum $Af\rho$ was calculated to be 216,300 cm, corresponding to a dust production rate of $Q_{\text{dust}} = 28,500$ kg s^{−1} and a total ejected dust mass $M_{\text{dust}} = 1.39 \times 10^{12}$ kg. These values exceed those reported by Lin (2023) for the same outbursting event; however, their dataset does not capture the earlier, more intense outburst identified in this study. Dust production exceeds values estimated by Fulle (1992) and Moreno (2009), but this is not unexpected as this particular outburst was the most energetic for over 20 years.

On the whole, these results support a picture of 29P/SW1's activity where outbursts are categorised into three intensity groups that likely reflect multiple outbursting mechanisms.

The annual outburst rate (~ 15.3 yr^{−1} for $\Delta m > 0.2$ mag) and infrequent quiescent periods ($> 80\%$ active) are consistent with a persistent, dust-rich coma resupplied by a *volatile* reservoir within the large nucleus.

Outbursts become bluer during the surge period, as the $g' - r'$ index decreases as brightness increases, and a quicker decrease in brightness following the outburst's peak in the g' -band compared to other filters, suggesting that gas dominates the coma early during the start of the outburst period and expands more rapidly than dust.

The shortest decay timescale ($\tau_{\min} \approx 3.1$ d) and the clustering of colour indices for the brightest data points further suggest that gas escapes rapidly while the dust remains within the photometric aperture for longer.

Overall, outburst mechanisms are compatible with both crystallisation of [AWI](#) into [CWI](#) and cryovolcanism, with the crystallisation likely driving the frequent minor and moderate outbursts, while cryovolcanism could explain the rarer, intense major outbursts.

9.1.1 Limitations

One of the principal limitations of this (extensive) dataset is the lack of data obtained during the surge period of outbursts. This is a short period of time, and it is difficult to obtain images from the [LCO](#) network as soon as an outburst is detected due to network scheduling. Increased observing cadence could constrain the true surge time of an outburst, giving further insight into the surge rate and if it is comparable with other outbursts types, i.e. major, moderate, and minor.

Monitoring colour index variation is only possible with multi-band observations. Multi-band images have been obtained since 2020 with the [LCO](#) network, though more near-simultaneous images could greatly improve understanding of colour evolution during an outburst. Obtaining near-simultaneous multi-band observations are important as variations are small and change rapidly.

Multiple outbursts detected by Miles (2024b) were not detected in this study. These were primarily due to the intensity being below the noise level. For example, Miles detected 24 outbursts during the 2022/23 apparition, while this study

only identified 12. Additionally, Miles uses amateur astronomer data, which was obtained at a far higher observing cadence, giving a clear indication that an outburst occurs due to multiple congruent measurements, instead of a single anomalous point found in this dataset. This biases the outburst rate downwards, and mean magnitude upwards.

9.1.2 Future Work

Future research can extend and refine these findings by addressing observational limitations, exploring rotational patterns, and developing more comprehensive outburst characterisations.

Further observations, both in frequency and duration (for future apparitions), could provide more detailed data for an outburst, allowing more precise surge and decay rate calculations and better measurement of colour variation.

Analysis of future apparitions may clarify the apparent seasonality that [29P/SW1](#) exhibits. The 2025/26 apparition, occurring one orbital period after the distinct ~ 57 d outbursting frequency reported by Miles et al. ([2016](#)), offers an opportunity to test whether similar periodicities re-emerge.

Further investigation of the rotational period could show if it is linked to the outbursting frequency. Using machine learning on outburst dates to identify outbursting periodicities could suggest whether the rotation is complex. This may help explain why calculating a consistent rotational period has varied between studies. If a relation is found between outburst frequency and rotational period, it would suggest that there are discrete sources for these outbursts.

Investigating each outburst in detail, characterising colour variation, coma morphology, and ejecta velocity, could give further insights into the mechanism(s) driving the outburst. A systematic catalogue of outburst evolution could help discern differences between outburst types. Identifying if outbursts have varying proportions of dust and gas could potentially aid in deducing the mechanisms behind different outburst types.

By enhancing temporal coverage, clarifying rotational effects, and improving event-level characterisation, future work can build upon this study to produce a more complete and physically coherent model of [29P/SW1](#)'s activity.

9.2 Pedagogy

Students surveyed enjoyed science lessons, with an even greater enjoyment of learning about space. Enjoyment of science lessons and learning about space decreases from Year 4 to Year 6, consistent with age-related declines in enjoyment reported by Pell and Jarvis ([2001](#)) and Murphy and Beggs ([2003](#)). Targeting students with topics they would enjoy is likely to have positive effects on interest and awareness of different fields within [STEM](#). The decline in enjoyment of science lessons and learning about space could be due to reduced novelty in the topic as they age, or due to a shift away from practical activities, consistent with findings by Murphy and Beggs ([2003](#)).

Space was selected as the most popular science topic, with 'experiments' being the second most popular. Space was widely enjoyed by students who dislike science lessons, reporting that it was their favourite topic. Murphy and Beggs ([2003](#)) and Blankenburg et al. ([2016](#)) also found that experiments are beneficial to students, helping them remember concepts better than conventional science lessons. Given both preferences, integrating space topics into practical work is likely to appeal to a large proportion of students, potentially improving their engagement and enjoyment science as a topic.

Overall, > 70% of students in this study correctly identified stars, galaxies, and planets from images, though they struggled more when distinguishing comets and meteors. This uncertainty in identifying comets and meteors indicates an opportunity to address under-represented astronomical objects, both in school and in the media. Those who said they enjoyed science lessons, or learning about space, were more likely to correctly identify the astronomical objects.

Students were asked about their desired job, with their responses categorised. [STEM](#) jobs were most popular for students in Years 4–6, followed by jobs in sport and art. [STEM](#) subjects were not the most popular, with Art being the most popular subject in school. Art being the most popular subject suggests that children gain great enjoyment of creative activities, a subject which deviates from conventional school lessons. Additionally, a student's favourite subject did not strongly correlate with their desired job, other than for careers in sport and art, suggesting decisions may be influenced by factors beyond their preferred subject. There could be a disconnect between school subjects and how they could lead into careers.

Few students mentioned that they knew someone who worked in the [STEM](#) field. Most cited knowing extended family members or family friends who worked in the [STEM](#) field. Very few students had a relation within their immediate family who worked in a [STEM](#) field - see table 5.7 for numbers. Having role models in [STEM](#) is associated with whether a student pursues a career in the field, as discussed by Siregar and Rosli (2021) and Stefani (2024). Introducing students to scientists could encourage uptake of these subjects later in their academic life. Exposure to relatable role models can nurture increased interest in the subject and a desire to pursue a career in [STEM](#) (Gladstone and Cimpian 2021). It is possible that students are simply not aware of what a 'science job' is. Multiple factors could contribute, including limited science capital; limited knowledge of what is classed as a [STEM](#) job; unclear survey wording.

Overall, the Comet Chasers' workshops were well received. Students reported high enjoyment and rated the overall programme quality positively. These positive impressions were consistent with the trial workshops at Radnor Primary School and with the school-based sessions delivered during the second phase of the programme.

Students in Year 4 and Year 6 reported higher general enjoyment than those in Year 5. A similar pattern was observed for the [IR](#) camera and Rotato activities. One possibility is that adaptations made to suit younger and older year groups

may have been less well-matched to Year 5 cohorts – particularly in mixed-year classes – thereby moderating their enjoyment.

Interpretation of Year 4 ratings should be cautious: the sample was small and may over-represent students with a pre-existing interest in space and science. Even so, Year 5 enjoyment scores were positive (3.7/5) and only modestly lower than Year 4 and Year 6 (4.1/5 and 4.2/5 respectively).

The highest-rated activity for enjoyment was the IR camera activity, with a mean rating of 4.2 out of 5; students in Year 4 rated it highest relative to other year groups.

This is a hands-on practical activity, with students using IR cameras to explore heat sources within their classroom. Of the three activities, the IR camera activity is the least structured and requires students to take the lead in their investigations. This gives students opportunities to be curious and try to problem solve independently. Susiloningsih et al. (2025) note that interactive activities improves students' critical thinking and creativity.

Meteorite handling was given an enjoyment rating of 4.1 out of 5. Each year group enjoyed this activity roughly equally, with Year 4 and Year 5 respondents rating 4.1 out of 5, with Year 6 students' enjoyment rating slightly lower, 4.0 out of 5. Participants conducted simple tests on the samples to explore indicators of composition (stone vs metal) and likely origin (meteorite vs tektite). They examined visual appearance, apparent weight, and magnetic response. In the post-engagement survey, students frequently commented that learning about the meteorites' ages was particularly interesting, and many reported wanting to handle additional samples.

The Rotato experiment was the least popular activity of the three, yet still had a positive enjoyment rating (3.7/5). Students in Year 6 rated their enjoyment the highest, with 67% awarding scores of 4 or 5. This activity is the most structured of the three and requires patience and critical thinking: students interpret variations in reflected light as an object rotates on a turntable, as seen on

the computer. In post-engagement feedback, students reported that they had learned about the behaviour of light in this context and how to interpret simple graphs.

The Rotato activity explains abstract astronomical concepts effectively, particularly how rotational lightcurves are generated and how reflected light varies with object shape, colour, and material. However, the method of delivery was not optimal for maintaining students' concentration and maximising learning. In the workshops presented here, students moved between activities part-way through the session, which potentially resulted in fragmented engagement for this more cognitively demanding task.

Compared with the other two activities, the Rotato is also the least visually stimulating: the IR camera activity provides access to unfamiliar equipment, and meteorite handling allows students to work with real samples, both of which capture attention more readily.

Students were frequently distracted whilst undertaking the Rotato experiment, especially those who began the workshop with this activity. Classroom observations suggest that Rotato would be better suited to a dedicated workshop, with the whole class completing the activity in groups and using the pre-set challenges (Appendices C and D) to provide a clearer structure and a sustained focus.

Holding Rotato as a separate session would also benefit the IR camera and meteorite-handling activities, allowing additional time to explore their respective learning outcomes. However, this revised format would require additional classroom time.

Taken together, these pedagogical findings suggest that students have positive impressions about science, especially when learning about space or conducting experiments.

Despite STEM careers being the most popular job category, there was little correlation with a students' favourite subject, suggesting that additional factors

contribute to a students' career aspiration at this age. Feedback from the Comet Chasers' workshops shows that interactive and exploratory activities are especially engaging, with students responding most positively to tasks that allow independent, curiosity-driven active investigation.

Overall, the results point to the value of combining space-based content with practical activities to support interest, enjoyment, and early awareness of STEM pathways.

9.2.1 Limitations

Nonetheless, these pedagogical results must be interpreted with caution, and a number of limitations should be kept in mind.

The sample sizes for the pre- and post-engagement surveys were relatively low ($N = 154$ and $N = 75$, respectively). However, this study was designed specifically for

Welsh-medium primary schools, which represent only around one third of all primary schools in Wales. Consequently, the total population of Welsh-speaking pupils in Years 4 to 6 is substantially smaller than the equivalent UK-wide cohort, making these response numbers proportionally more meaningful within the intended population. Moreover, very few STEM-engagement or physics-education studies have been conducted exclusively within Welsh-medium settings, and no previous work was identified that examines Welsh-language pupils' participation in a dedicated STEM outreach programme. Although the sample is small in absolute terms, the study provides a rare and valuable insight into STEM engagement among Welsh-medium learners, offering evidence that is both contextually appropriate and uniquely positioned within the existing literature.

Not all schools where interventions were conducted completed the surveys, with only two schools completing both. Survey completion depended on teacher facilitation and was carried out after the workshop presenter had left the school, which may have reduced the consistency of participation across sites.

A further limitation relates to workshop delivery. All workshops were conducted with only one presenter, which may have limited the support available to students during activities, particularly during times requiring guidance or technical issues.

Sampling bias may have influenced the responses received. Teachers were responsible for selecting students to take part in the workshops. Some schools requested multiple workshops for different classes, while for smaller schools, a whole year group could take part in a single workshop. It is possible that some schools selected the students with higher pre-existing interest who may have been preferentially selected.

Mixed-year groups could have inadvertently disadvantaged students within the minority year group. For example, adaptations may be made to the delivery of a workshop to either a group consisting mainly of students in Year 4 or Year 6, potentially leaving students in Year 5 somewhat isolated. It is possible that students may not have enjoyed the workshop as much as possible as the target age for delivering the workshop had shifted slightly.

Finally, survey wording may have created confusion or uncertainty in the students when responding. Casual language was used with the aim of improving accessibility, regional variation in the Welsh language and differences in age-related vocabulary could have influenced how students interpreted particular questions.

9.2.2 Future Work

Building on the insights of this study, future work could refine these findings and further develop the successes of the Comet Chasers' programme both in English and Welsh.

As the sample size was limited, and did not consist of a broad range of different schools, additional workshops with students completing pre- and post-engagement surveys would be beneficial.

Focusing on interventions in urban schools to compare their pre-engagement responses with those received in this study from rural schools, this could highlight science capital differences between these areas.

Additionally, conducting workshops in English-medium schools in rural areas, and Welsh-medium schools in urban areas, could give further insight into whether a difference in science capital exists because of where a student lives or if it is due to the language spoken at school, or at home. Responses from these schools would give a richer view into how [STEM](#) education varies in Wales.

Regarding the Rotato experiment, changes should be made to the software used to address the issues mentioned in survey responses. This would result in ‘easier to use’ software, with quality-of-life additions to aid students. Having workshops dedicated solely to the Rotato could improve focus by reducing the distractions from other activities, create a more structured learning environment, and encourage collaboration with their peers whilst all participating in the same activity.

More presenters are required to conduct interventions, as having only a single presenter risks not being able to address issues that students may have during the activities.

Multiple (thematically connected) interventions at the same school could also aid student enjoyment and learning, fostering a relationship between the students and presenter, allowing the presenter to be viewed as an approachable role model. This would allow the introduction of additional activities and astronomical concepts, broadening the students’ awareness of such topics.

Developing a supplementary, complete Comet Chasers’ package, consisting of worksheets and teacher guides, would let teachers use the content during conventional lessons. Availability of ‘expert’ presenters would then no longer be an issue and could create a more structured lesson compared to the presenter-led workshops trialled here.

Using the schools taking part in the Comet Chasers programme to regularly image different astronomical objects of interest would benefit comet researcher's work. Comets and asteroids, unlike stars and galaxies, are more prone to changes to their orbits or behaviours, requiring a higher cadence of observations to study these changes. The huge number of [29P/SW1](#) observations made by Comet Chasers schools has enabled a detailed and thorough investigation into outburst trends, as outlined in previous chapters. This approach can, and should, be applied to other objects to increase images obtained for more detailed investigations.

Overall, pursuing these developments would provide a more detailed understanding of [STEM](#) engagement across different school settings in Wales, while strengthening the impact and accessibility of the Comet Chasers' programme.

Chapter 10

Conclusion

This thesis set out to characterise and identify trends in the outbursts of the Centaur [29P/SW1](#) using data obtained by school students participating in the Comet Chasers STEM outreach programme. It also examined Welsh-medium pupils' enjoyment of science lessons, space, and the Comet Chasers workshops as a means of engaging them with STEM topics. Building on the analysis presented in the preceding chapters, this conclusion summarises the key findings from both strands of the research and offers the final concluding remarks.

10.1 Key Results

1. Outbursting Frequency and Categorisation

- Typically 15.3 ± 1.0 outbursts of $\Delta m > 0.2$ mag are expected to occur each year.
- Three distinct outbursting groups were detected: major ($\Delta m \geq 2.5$ mag), moderate ($1.0 \leq \Delta m < 2.5$ mag), and minor ($\Delta m < 1.0$ mag).
- 46% of outbursts detected were minor outbursts, with moderate outbursts making up 38%, and 14% of outbursts being major. This proportion varies between apparitions, with no major outbursts occurring

during the 2019/20 apparition, this coincided with the greatest number of minor outbursts detected. The Centaur is in an active state for 84% of the time.

- A nuclear reduced magnitude in r' -band observations was found to be $R(1, 1, 0) = 9.68 \pm 0.41$ mag. This corresponds to a nuclear radius of $r_N = 37.3 \pm 11.0$ km.

2. Variations and Trends During Outbursts

- The $g' - r'$ index decreases by -0.25 ± 0.30 mag on average during the surge period of an outburst, while the $r' - i'$ index does not vary much during this period, -0.01 ± 0.08 mag. The object becomes bluer and is indicative of unital gas-dominated coma expansion at the start of the outburst.
- Mean decay rate calculated to be 0.10 ± 0.10 mag d⁻¹. For more intense outbursts this value increases, with the mean decay rate of major outbursts being 0.18 ± 0.17 mag d⁻¹.
- Mean colour indices for the whole dataset were calculated to be: $g' - r' = 0.51 \pm 0.01$ and $r' - i' = 0.27 \pm 0.01$. The $g' - i'$ index is similar to the solar value, while the $r' - i'$ index is over twice the solar value. This increase in the $r' - i'$ implies a dust-rich coma for the majority of the time. When the Centaur is at its brightest, both colour indices tend to decrease.
- Gas expansion velocity was estimated to be $v_{gas} \sim 0.4$ km s⁻¹. Dust ejected velocity was estimated to be $v_{dust} < 0.1$ km s⁻¹.

3. Science Capital of Students in Rural Areas of Wales

- Students in Welsh-medium, rural schools enjoy science lessons and learning about space. Enjoyment decreases as students age, agreeing with previous studies focussing on different countries.

- [STEM](#) careers were the most popular category of job. A students' favourite subject in school does not have great influence on their future desired job. Those who have relations working in a [STEM](#) field were not more likely to opt for a future career in [STEM](#) at this age.
- Space was selected as the most popular topic within science. It was selected by students who enjoyed and disliked science lessons, suggesting a broad appeal.

4. Activities to Maximise Student Enjoyment

- Interactive and exploratory activities were most enjoyed. Practical activities engaged students with the concepts presented.
- The [IR](#) cameras activity was most popular. This activity involves the students in independent investigation and collaboration. It uses unfamiliar and exciting equipment and an unstructured activity, contributing to students' enjoyment.
- Rotato experiment would work better as a stand-alone workshop, with students collaborating to complete pre-set challenges. This could increase focus and enjoyment of the activity.

10.2 Concluding Remarks

In conclusion, this research set out to initiate the characterisation of [29P/SW1](#)'s outbursts and to identify recurring features across different events, with the long-term goal of improving our understanding of the mechanisms which drive these violent episodes. In parallel, it explored students' enjoyment and responses to participating in astronomy-based activities, looking toward a future in which more schools contribute observations of astronomical objects (as was the case here, with the Comet Chasers programme).

The results demonstrate that [29P/SW1](#)'s outbursts can be categorised by their intensity and that consistent patterns emerge in their colour evolution and in

both surge and decay rates. These findings provide a foundation for further characterisation that may help unlock the underlying mechanisms responsible for triggering outbursts. Continued high cadence observations of future apparitions are essential to determine if the Centaur's activity exhibits seasonality due to its rotational inclination angle, and to assess whether outbursts can be accurately predicted.

This work was largely made possible by the volume and quality of the images obtained through schools participating in the Comet Chasers programme. Engaging students in genuine astronomical research creates mutual benefit: students are introduced to real-world scientific collaboration, while astronomers obtain valuable additional observations. This collaborative method of data acquisition should continue for [29P/SW1](#) and be extended to other objects to support ongoing research.

Looking ahead, our understanding of cometary activity at large [heliocentric](#) distances will steadily improve through further ground-based and space-based observing, as well as in-situ missions. But there will always be an important role for observations made by amateur astronomers and, as demonstrated here, increasingly so by the contributions of school students working closely with researchers and accessing professional-quality equipment through innovative programmes like Comet Chasers. We have shown here that the data obtained through such educationally stimulating programmes, backed by a clear science goal, can contribute meaningfully to mainstream astronomical research.

Although Centaurs remain challenging to study due to their transitional nature, they are essential to revealing the evolutionary pathways of minor bodies in the [SS](#). This work represents an early step toward that broader understanding.

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Appendix A

Original Workshop Worksheets



METEORITES

NAME: _____

Does a magnet stick to it?

Yes ☒

No ☐

Maybe ☐

Describe it. What is it made of?

What do you think this is?

Why do you think this?

Draw a picture of it:

What is it? (Ask for help!)



ROTATO

NAME: _____

What makes the line rise? Put a circle around your answers.

Colour	Size	Texture
Black	Big	Shinny
White	Small	Dull

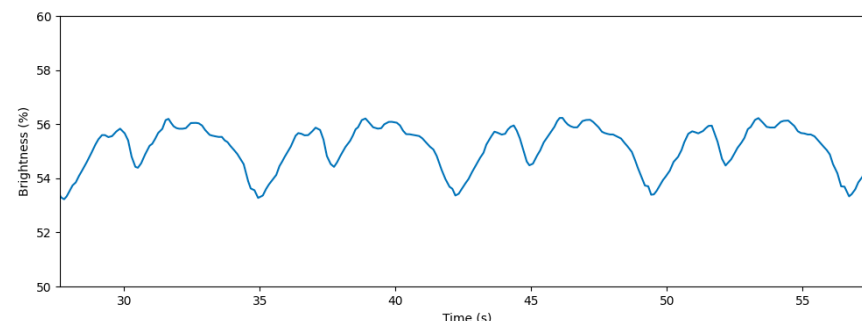
Draw a picture of the graff of any item turning:

Item:

Brightness

Time

What item do you think has caused this line?



How long does it take for the turntable to make one full rotation? Clue: look at how the lightcurve patter changes and the times.

S



INFRARED CAMERA

NAME: _____

What is the hottest thing in the room?

Item:	Temperature: °C
-------	-----------------

What is the coldest thing in the room?

Item:	Temperature: °C
-------	-----------------

Which bottle has the hot water in it? (WITHOUT TOUCHING THE BOTTLE!)

A

B

What part of the body is the hottest and coldest?

Hottest:	Coldest:
----------	----------

Make a drawing of someone wearing glasses while looking through the infrared camera:

A large, empty rectangular box with a thick black border, intended for a drawing of a person wearing glasses and looking through an infrared camera.

Appendix B

Activity Help Sheets



METEORITES



Rocks from space

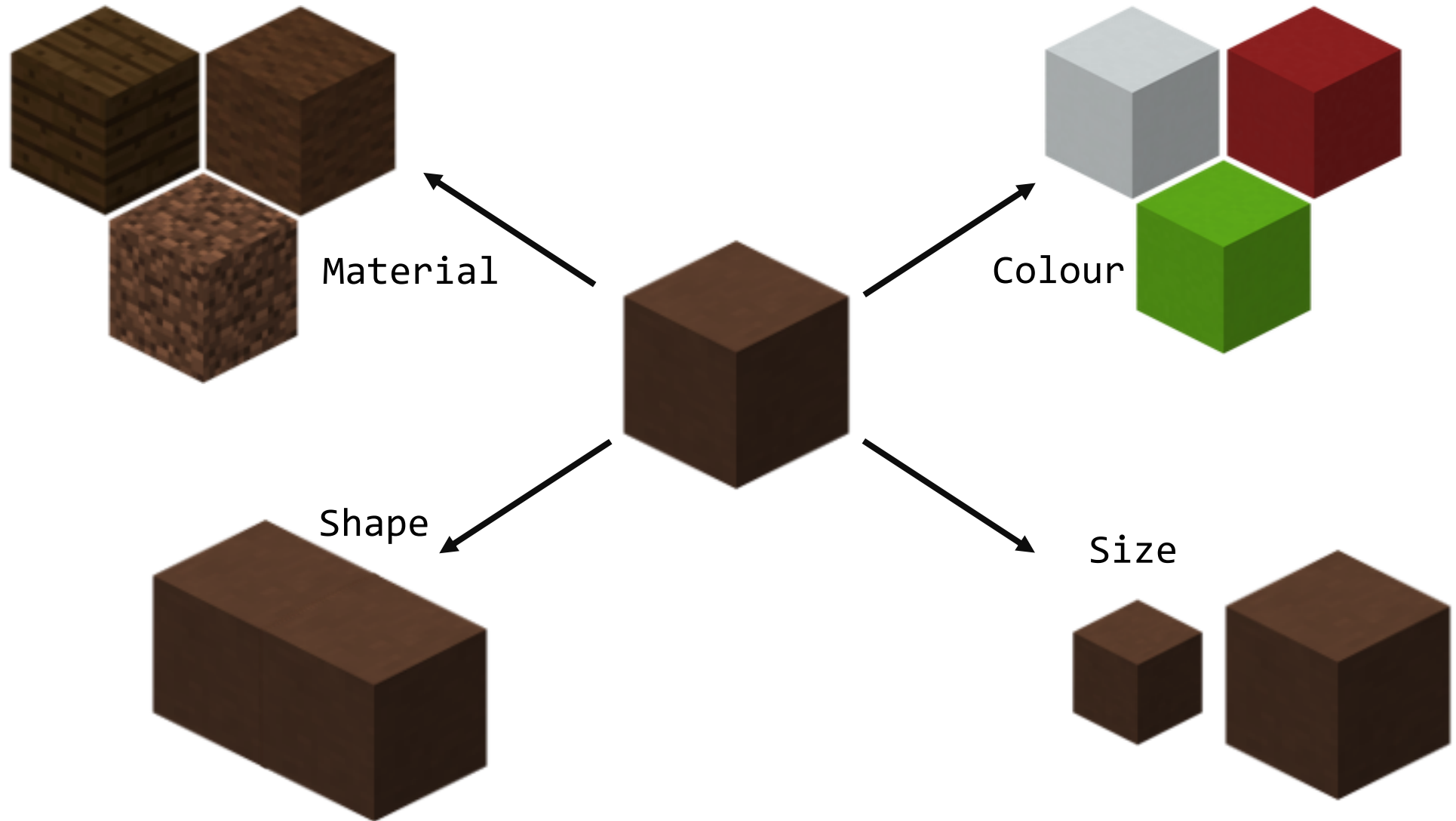
Rock or Metal

TEKTITES



Glass made from melted sand
after a meteorite lands

WHAT CAUSES THE LIGHT CURVE TO CHANGE?



HOW TO USE THE ROTATO

Brighter

Less
bright

Start/Stop
plotting
the light
curve

Reset the
light curve.
Get rid of
the light
curve.

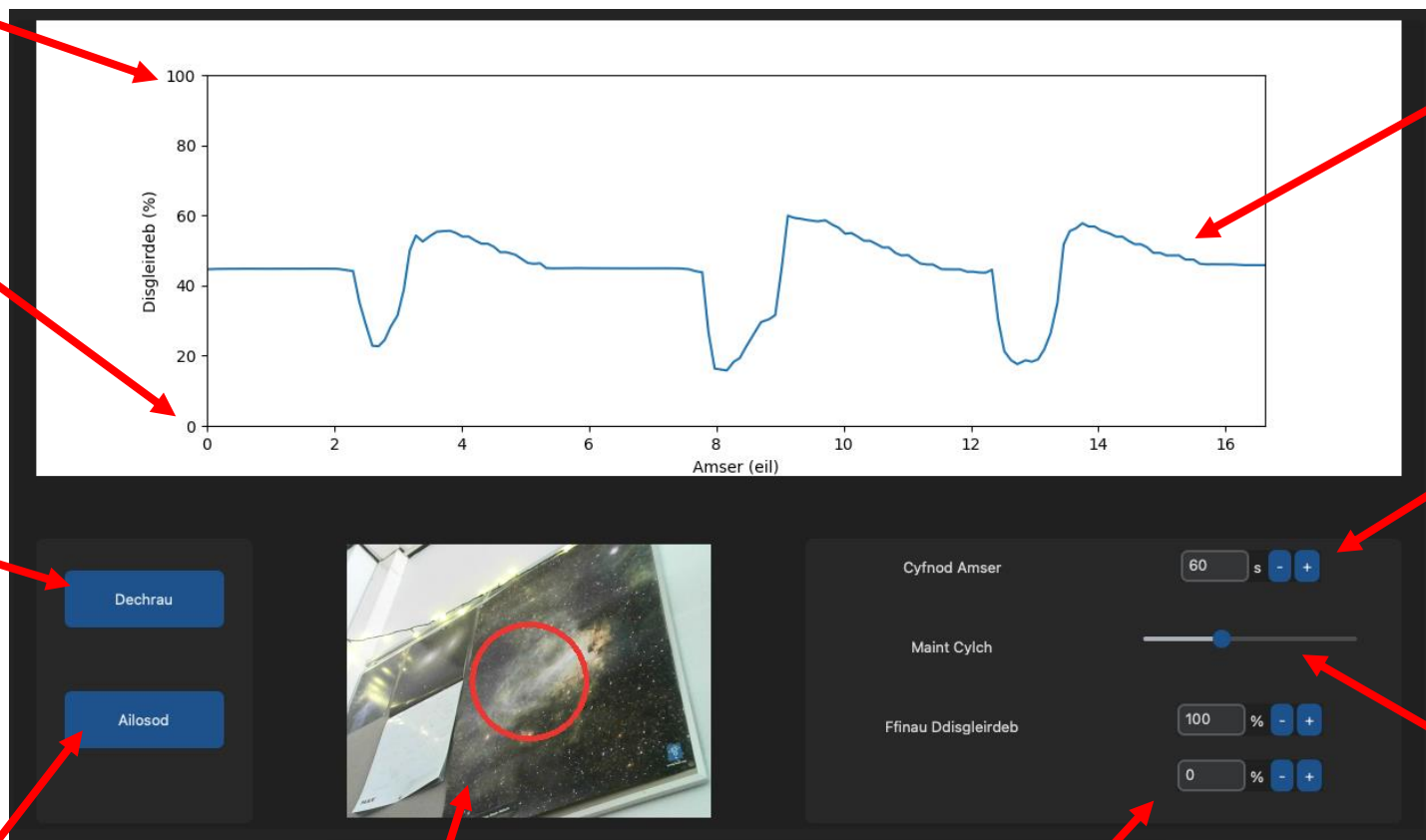
Video of the web cam.
Click on the video to
change the location of
the circle.

Change how
zoomed-in the
graph is.

Light
curve

Change the
time period
that scrolls

Change the
circle size to
measure the
brightness



Appendix C

Rotato Mission 1



Mission 1:

Measuring Brightness

Comets and asteroids don't create light like stars do, they can only reflect the light from stars. By measuring this reflected light, astronomers can learn a lot about the colour, size, and material of the object in space.

Phase 1: Colour

- Pick one black and one white cube – these will be your fake comets.
- Point the torch at the black cube – the torch represents the Sun.
- Aim the webcam at the cube – this is the telescope. Make sure that the cube is inside the red circle on the screen (hint: click on the video to move the circle).
- Press 'Start', leave it for a few seconds, then press 'Stop'.
- Repeat these steps with the white cube.

1) How does the line change after you swap the colours?
2) Which colour is brighter? (Which colour makes the line go higher on the graph?)
How do different colours compare with the black and white cubes?

Phase 2: Size

- Repeat the steps to **Phase 1** but use the large and small cube (instead of the white and black cubes).

4) How does the brightness change if you compare a large cube with a small cube?

Phase 3: Material/Texture

- Repeat the steps to **Phase 1** but use objects with different materials or textures (hint: use the shiny, felt, and painted cubes).

5) How does the brightness change if you compare objects with different materials?

Mission Debrief

Phase 1: Colour

The line for the white cube will be higher than for the black cube – this means that white is brighter than black.

The brightness of a colour depends on how much light is reflected. This means that white reflects more of the sunlight than black does.

Other colours will have a brightness between the brightness of the black and white cubes.

Phase 2: Size

The larger cube will be brighter than the smaller cube as there is more of the object to reflect the light.

Phase 3: Material/Texture

Shiny objects will appear brighter as it is very good at reflecting light.

The felt cube will be slightly dimmer than the painted cube as it has a texture which makes it harder for light to be reflected.



Appendix D

Rotato Mission 2



Mission 2:

Begin Rotating

Comets and asteroids in space rotate (they spin), so we always see different sides of them. This makes studying the object a bit harder, but it can also help us discover how fast the object rotates or even figure out its shape! Astronomers measure the brightness of the object and plot it on a graph against time - this graph is called a **light curve**. This is the graph on your computer screen.

Phase 4: Rotating Cube

- Pick a cube and place it on the turntable. Turn on the turntable by pressing the 'R/L' button. Speed can be controlled by pressing the 'SR' button.
- Point the torch and aim the webcam at the cube, make sure the red circle on the screen is around the cube.
- Press 'Start' on the computer. Wait for the cube to do a few full turns, after this, press 'Stop'.

- **How does the graph now look when the cube is rotating?**
 - **Why does this graph change as the cube turns?**

Phase 5: Different Shapes

- Swap the cube with a different shape and repeat Phase 4.

- **What's the difference between this graph and the graph for the cube?**
 - **Why do you think the graph looks like this?**
- **Which objects have the largest change in brightness as it rotates?**

Phase 6: Real Comets

- Swap the object with a 3D model of a comet and repeat Phase 4.

6) What are the brightest and dimmest parts of the comet?

Mission Debrief

Phase 4: Rotating Cube

The light curve (the graph) repeats itself after the cube does one full turn.

The brightness of the cube changes as it turns is because we sometimes see less of the cube (dimmer) and sometimes we see more of the cube (brighter).

Phase 5: Different Shapes

Different shapes have different light curves.

The objects with the largest differences in brightness would be shapes like cylinders (like a glue stick laying down) as we sometimes see the cap (which is small and dim) and sometimes see the edge (which is long and therefore bright).

Phase 6: Real Comets

The brightest part will be when we see the most of the comet, the dimmest will be when we see the least amount of the comet.



Appendix E

Teacher Participant Information

PARTICIPANT INFORMATION SHEET (TEACHER)

Catching Comets in the Land of Dragons/Cipio Comedau yng Ngwlad y Dreigiau

You are being invited to take part in a research project. Before you decide whether or not you want to take part, it is important for you to understand why the research is being undertaken and what it will involve. Please take time to read the following information carefully and discuss it with others, if you wish.

Thank you for reading this.

1. What is the purpose of this research project?

Comet Chasers is a project which brings outer space into the classroom. By working with professional and amateur astronomers, we can give a unique project which teaches students about how real science and astronomy works. In addition to resources and lessons, Comet Chasers gives schools access to a world-wide professional robotic telescope network (Las Cumbres Observatory). Schools are free to use this network to image comets, asteroids, stars, etc. and conduct their own analysis. If their images are used by professional astronomers to publish their research, the schools are credited on journal papers.

This study aims to evaluate resources and lessons that the Comet Chasers project has developed to better suit the needs of teachers and students. We will investigate if this 'hands-on' scientific approach aids in students' interest in science, physics and astronomy and development of their key skills. In addition, we will evaluate the effectiveness of the project conducted in Welsh and English and investigate if there are major differences in science between Welsh and English medium schools.

2. Why have I been invited to take part?

Your school wishes to be part of the Comet Chasers project. You have been invited as you are the teacher involved with the Comet Chasers programme. Your feedback on the programme will be used to improve existing and develop new resources.

3. Do I have to take part?

No, your participation in this research project is entirely voluntary and it is up to you to decide whether or not to take part.

If you decide to take part, we will discuss the research project with you and ask you to sign a consent form. This will include an agreement that you will distribute participant information and instructions how to opt-out to students' guardians at least 1 week before the Comet Chasers session.

If you decide not to take part, you do not have to explain your reasons and it will not affect your legal rights. Additionally, if you do not consent to the study, you can still run Comet Chasers lessons, but no feedback or evaluation will be obtained from you.

You are free to withdraw your consent to participate in the research project at any time, without giving a reason, even after signing the consent form. Despite this, any already anonymised data will not be able to be removed.

4. What will taking part involve?

We will ask you to complete questionnaires based on the resources, activities, and lessons. You will be asked about specific resources and activities, in addition to your opinions on student engagement and progress.

Focus groups may be run with you and (if applicable) other teachers involved with the Comet Chasers programme. These sessions will be audio recorded, transcribed omitting any identifiable data, and the audio file deleted.

You may use the website astro-tools.space during Comet Chasers sessions. If prompted, we ask that you review the tools after using them. This is entirely voluntary. This will give us your anonymous review regarding a tool's ease of use, functionality, and usefulness. In addition, the time taken to use each tool will be tracked – this data will be anonymous.

Additionally, we ask you to distribute participant information and information on how to opt-out of taking part in the study to the guardians of your students. These documents will be emailed to you.

5. Will I be paid for taking part?

No. You should understand that any data you give will be as a gift and you will not benefit financially in the future should this research project lead to the development of a new teaching method.

6. What are the possible benefits of taking part?

There will be no direct advantage or benefits to taking part, but your contribution will help us develop better resources and activities for future Comet Chasers interactions.

7. What are the possible risks of taking part?

There are no risks in taking part.

8. Will taking part in this research project be kept confidential?

All information collected from (or about) you during the research project will be kept confidential and any personal information you provide will be managed in accordance with data protection legislation. Please see 'What will happen to my Personal Data?' (below) for further information. Any questions have the option 'prefer not to answer'.

9. What will happen to my Personal Data?

Completed consent forms, and any printed personal data, will be stored by the lead researcher in Cardiff University School of Physics and Astronomy Office.

Digital personal data (such as audio recording) will be securely stored on university share-point file only accessible to the lead researcher and their supervisor.

You will be identified only as ‘Teacher at YOUR SCHOOL’. No identifiable information will be obtained. You are designated this ‘name’ to keep track of your responses throughout the study.

Cardiff University is the Data Controller and is committed to respecting and protecting your personal data in accordance with your expectations and Data Protection legislation. Further information about Data Protection, including:

- your rights
- the legal basis under which Cardiff University processes your personal data for research
- Cardiff University’s Data Protection Policy
- how to contact the Cardiff University Data Protection Officer
- how to contact the Information Commissioner’s Office may be found at www.cardiff.ac.uk/public-information/policies-and-procedures/data-protection

Printed copies and accessible versions of the above-mentioned documentation and privacy notices are available at request.

No personal or identifiable data will be shared. Responses to teacher questionnaires and focus groups will be shared with Helen Usher, a member of the Comet Chasers team and PhD student at the Open University – this data will be wholly anonymous.

The research team will immediately anonymise all personal data that has been collected from, or about, you in connection with this research project, except for the school’s consent form. Anonymised information will be kept for a minimum of 5 years following the completion of the study but may be published in support of the research project and/or retained indefinitely, where it is likely to have continuing value for research purposes.

If you wish to withdraw your consent from this study, all personal and identifiable data will be immediately destroyed. Digital data will be deleted, and non-digital data will be shredded. Data will be anonymised after 1 month after the first Comet Chasers interaction, while some questionnaires will be immediately anonymised. Note that it will not be possible to withdraw any anonymised data that has already been published or in some cases, where identifiers are irreversibly removed during the course of a research project, from the point at which it has been anonymised. Please contact the lead researcher Cai Stoddard-Jones (Stoddard-JonesIC@cardiff.ac.uk) or the Cardiff University School of Physics and Astronomy Office to withdraw your consent.

10. What happens to the data at the end of the research project?

Data obtained from this study will be used in the lead researcher’s PhD thesis. No identifiable data will be included, and all participants will be given an anonymous designation if their feedback is included. Data will be used to improve existing and create new resources and activities to best suit teacher and student needs.

Data will be shared with Comet Chasers team member and Open University PhD student, Helen Usher. Helen is conducting her own research into Comet Chasers resources. Data shared will be wholly anonymous.

11. What will happen to the results of the research project?

It is our intention to publish the results of this research project in the researchers' theses, academic journals, and present findings at conferences. Participants will not be identified in any report, publication or presentation. Verbatim quotes from participants may be used. Results will be used to improve Comet Chasers resources and activities.

12. What if there is a problem?

If you wish to complain or have grounds for concerns about any aspect of the manner in which you have been approached or treated during the course of this research, please contact Cai Stoddard-Jones (Stoddard-JonesIC@cardiff.ac.uk).

If your complaint is not managed to your satisfaction, please contact the Chair of the PHYSX Research Ethics Committee, Dr Timothy Davis (DavisT@cardiff.ac.uk).

If you are harmed by taking part in this research project, there are no special compensation arrangements. If you are harmed due to someone's negligence, you may have grounds for legal action, but you may have to pay for it.

13. Who is organising and funding this research project?

The research is organised by Cai Stoddard-Jones in the School of Physics and Astronomy at Cardiff University, supervised by Prof. Paul Roche.

14. Who has reviewed this research project?

This research project has been reviewed and given a favourable opinion by the PHYSX Research Ethics Committee, Cardiff University.

15. Further information and contact details

Should you have any questions relating to this research project, you may contact us during normal working hours:

Cai Stoddard-Jones

N/3.29, Queen's Buildings – North Building, 5 The Parade, Newport Road, Cardiff, CF24 3AA
Stoddard-JonesIC@cardiff.ac.uk

Thank you for considering taking part in this research project. If you decide to participate, you will be given a copy of the Participant Information Sheet and a signed consent form to keep for your records.

Appendix F

Teacher Consent Form

CONSENT FORM - TEACHER

Title of research project: Catching Comets in the Land of Dragons/Cipio Comedau yng Ngwlad y Dreigiau

SREC reference and committee: s_2022-12-20_Stoddard – School of Physics and Astronomy Research Ethics Committee

Name of Chief/Principal Investigator: Cai Stoddard-Jones

**Please
initial box**

YOUR PARTICIPATION	
I confirm that I have read the information sheet labelled 'TEACHER' dated 26/02/2024 version 5 for the above research project.	
I confirm that I have understood the information sheet labelled 'TEACHER' dated 26/01/2024 version 5 for the above research project and that I have had the opportunity to ask questions and that these have been answered satisfactorily.	
I understand that data collected during the research project may be looked at by individuals from Cardiff University or from regulatory authorities, where it is relevant to my taking part in the research project. I give permission for these individuals to have access to my data.	
I understand that participation is voluntary, and I am free to withdraw at any time without giving a reason and without any adverse consequences.	
I consent to the processing of my personal information for the purposes explained to me: this consent form and audio recording. I understand that such information will be held in accordance with all applicable data protection legislation and in strict confidence, unless disclosure is required by law or professional obligation.	
I understand who will have access to the personal information provided, how the data will be stored, and what will happen to the data at the end of the research project.	
I consent to being audio recorded for the purposes of the research project and I understand how it will be used in the research.	
I understand that anonymised excerpts and/or verbatim quotes from focus groups or questionnaires may be used as part of the research publication.	
I understand how the findings and results of the research project will be written up and published.	
I agree to take part in this research project	
SCHOOL PARTICIPATION	
I agree to distribute the information sheet labelled 'GUARDIAN' dated 26/02/2024 version 2 to students' guardians at least 1 week before the Comet Chasers session.	
I agree for the school to take part in this research project.	

Name of participant (print)

Date

Signature

School name (print)

Cai Stoddard-Jones

Name of person taking consent

Date

Signature

Lead researcher

Role of person taking consent

THANK YOU FOR PARTICIPATING IN OUR RESEARCH

Appendix G

Guardian Participant Information

Catching Comets in the Land of Dragons

1. What is the purpose of this research project?

Comet Chasers (CC) is a project bringing space to the classroom. We work with professional and amateur astronomers to teach students about how real science and astronomy works. We want to see if the lessons and activities help and work well for teachers and students. We'll look at if a 'hands-on' method of learning makes students more interested in science, physics, and astronomy, and helps teach important skills. Also, we'll be looking at differences in Welsh and English science education to see if there is a difference between Welsh and English language schools.

2. Who's doing this research?

This research project is organised by Cardiff University PhD student Cai Stoddard-Jones. This research project has been reviewed and approved by the PHYSX Research Ethics Committee, Cardiff University. If you have any questions or complaints, please contact Cai Stoddard-Jones (Stoddard-JonesIC@cardiff.ac.uk) or the Chair of the PHYSX Research Ethics Committee, Dr Timothy Davis (DavisT@cardiff.ac.uk).

3. What do we want to find out?

We want to know if doing real-life science activities makes students more interested in science subjects. Also, we want to see how Welsh and English language students react to these activities. We'll ask your child to fill in questionnaires (and maybe focus groups) before and after the activities.

Filling in a questionnaire or taking part in a focus group is **completely voluntary**, your child doesn't have to take part in anything you or they don't want to. Questionnaires will ask for your child's school year, school, gender, what languages they speak, are their family into science, also their opinions on the CC activities. All questions will have the option 'Prefer not to answer'. All your child's answers will be private, and we won't know whose answers are whose.

4. What will happen to my personal data?

The answers your child gives will be stored on a secure server provided by the university. This folder can only be accessed by the lead researcher (Cai Stoddard-Jones) and their supervisor. After the project has finished, the answers will be stored for 5 years. Then, answers you give with computers will be deleted, and any paper copies will be shredded.

5. How do I opt-out?

This research project uses an **opt-out system**. Your child's school has agreed to take part in this project. If you don't want your child to take part, please follow this link (forms.office.com/e/hGQc53pKu3), or scan the QR code at the bottom of the page, and complete the form to opt-out. If you opt-out, your child will still be able to take part with the CC activities in class.



For full participant information on this project, please visit shorturl.at/Lym1Z. If you have any questions about this study, please contact during normal working hours:

Cai Stoddard-Jones

N/3.29, Queen's Buildings – North Building, 5 The Parade, Newport Road, Cardiff, CF24 3AA
Stoddard-JonesIC@cardiff.ac.uk

Appendix H

Pre-Engagement Survey

Holiadur Ysgolion Cipwyr Comedau (Gynradd)

Diolch am cymryd yr amser i gwblhau yr holiadur yma.

* Required

⋮

1

Pa blwyddyn ysgol wyt ti mewn? *

- ☐ Blwyddyn 4
- ☐ Blwyddyn 5
- ☐ Blwyddyn 6
- ☐ Dim eisiau ateb

2

Pa ysgol wyt ti'n mynd i? *

3

Pa fath o swydd wyt ti eisiau pan ti'n tyfu i fyny? *

4

Wyt ti'n adnabod rhywun sydd yn gweithio yn gwyddoniaeth? *

- ☐ Ydw
- ☐ Nag ydw
- ☐ Dim yn siwr

5

Pwy wyt ti'n gwybod sydd yn gweithio mewn gwyddoniaeth?

- ☐ Rhiant/Gwarchodwr
- ☐ Brawd/Chwaer
- ☐ Other family member (Grandparent, Uncle/Aunt, cousin) Aelod teulu arall (nain/taid, ewythr/modryb, cefnder/cyfnither)
- ☐ Ffrind o'r teulu

6

Beth ydi dy hoff pwnc yn ysgol? *

- ☐ Hanes
- ☐ Gwyddoniaeth
- ☐ Technoleg Gwybodaeth (defnyddio cyfrifiaduron)
- ☐ Saesneg (darllen, ysgrifennu)
- ☐ Cymraeg (darllen, ysgrifennu)
- ☐ Celf (paentio, cerddoriaeth, llunio)
- ☐ Addysg Gorfforol (chwaraeon, ymarfer)
- ☐ Mathemateg
- ☐ Other

7

Wyt ti'n mwynhau gwersi gwyddoiaeth? (1 = dim o gwbl, 5 = caru nhw) *

- ☐
- ☐
- ☐
- ☐
- ☐

8

Pa rhan o gwyddoniaeth wyt ti'n hoffi'r mwyaf? *

- ☐ Anifeiliaid a phlanhigion
- ☐ Y gofod
- ☐ Arbrofion
- ☐ Y corff
- ☐ Cyfrifiaduron
- ☐ Other

9

Wyt ti'n mwynhau dysgu am y gofod? (1 = dim o gwbl, 5 = caru nhw) *



10

Wyt ti eisiau dysgu mwy am y gofod yn ysgol? (1 = dim o gwbl, 5 = rili eisiau dysgu mwy) *



Matchiwch y beth yn yr gofod gyda rhif y llun. *

Beth yw'r pethau yma yn y gofod yn y lluniau yma?

1



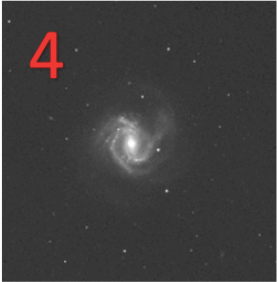
2



3



4



5



	Comed	Galaeth (Galaxy)	Meteorau (Meteors)	Planed	Sêr
1	☐	☐	☐	☐	☐
2	☐	☐	☐	☐	☐
3	☐	☐	☐	☐	☐
4	☐	☐	☐	☐	☐
5	☐	☐	☐	☐	☐

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Appendix I

Post-Engagement Survey

Holiadur Cipwyr Comedau (ar ol y sesiwn)

Holiadur cyflym i weld be oeddach yn meddwl am y sesiwn Cipwyr Comedau. Atebwch yn onest os gwelwch yn dda.

1. Pa flwyddyn ysgol wyt ti?

- ☐ Blwyddyn 4
- ☐ Blwyddyn 5
- ☐ Blwyddyn 6
- ☐ Dim eisiau ateb

2. Be ydi enw dy ysgol?

Rotato

Mae'r cwestiynau yma i gyd am yr arbrawf 'rotato'.

3. Wnes ti mwynhau gwneud yr arbrawf 'rotato'? (1 gwyneb=dim o gwbl, 5 gwyneb=caru fo!)



4. Be wnes ti dysgu wrth ddefnyddio'r 'rotato'?

5. Be oedd y rhan orau o'r 'rotato'?

6. Be wnes ti ddim hoffi am y rotato?

7. Wnaeth y 'rotato' helpu ti deallt sut mae seryddwyr yn ddeall comedau?

- ☐ Do
- ☐ Naddo
- ☐ Dim yn siwr

8. Oedd y meddalwedd (software) rotato ar y cyfrifiadur yn hawdd i ddefnyddio?

- ☐ Oedd
- ☐ Nag oedd
- ☐ Dim yn siwr

9. Be wnes ti ddim hoffi, neu ffeindio'n anodd, gyda'r meddalwedd (software) rotato ar y cyfrifiadur?

Camerâu IG

Mae'r cwestiynau yma i gyd am y camerâu is-goch.

10. Wnes di mwynhau defnyddio'r camerâu IG? (1 gwyneb=dim o gwbl, 5 gwyneb=caru fo!)



11. Be wnes ti dysgu wrth ddefnyddio'r camerâu IG?

12. Be oedd y rhan orau o ddefnyddio'r camerâu IG?

13. Be wnes ti ddim hoffi am y camerâu IG?

Meteorynnau

Mae'r cwestiynau yma i gyd am y meteorynnau.

14. Wnes ti mwynhau gafael ac arbrofi ar y meteorynnau? (1 gwyneb=dim o gwbl, 5 gwyneb=caru fo!)



15. Be wnes ti dysgu wrth gwneud arbrofion ar y meteorynnau?

16. Be oedd y rhan orau o'r meteorynnau?

17. Be nes di ddim hoffi am y meterorynnau?

Cipwyr Comedau

Cwpl o gwestiynau olaf am y sesiwn ar y cyfan.

18. Wnes ti mwynhau y sesiwn Cipwyr Comedau? (1 gwyneb=dim o gwbl, 5 gwyneb=caru fo!)



19. Be wnes ti mwynhau y mwyaf o'r sesiwn?

20. Be wnes ti ddim mwynhau am y sesiwn?

21. Sut fedra ni gwellau Cipwyr Comedau?

22. Oedd yna rywbeth wnes ti ddim deall yn ystod y sesiwn?

23. Fysa ti yn hoffi helpu Cipwyr Comedau gan ddefnyddio telesgopau ar draws y byd i gymryd lluniau o comedau?

- ☐ Ia
- ☐ Na
- ☐ Dim yn siwr

24. Faint o sêr ti'n rhoi i Cipwyr Comedau (1 seren=dim yn dda o gwbl, 5 seren=ffantastic)



25. Fysa ti'n hoffi gwneud mwy o gweithgareddau gyda Cipwyr Comedau?

- ☐ Oes
- ☐ Nag oes
- ☐ Dim yn siwr

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Appendix J

Outburst Summary

Label	Start Date	m_{start}	Peak Date	m_{peak}	Δm	Obs	Max T_{surge}	Min T_{surge}	End Date	m_{end}	T_{decay}
2016-A	05/06/2016 11:07	16.30	07/06/2016 12:37	14.39	1.91	3	2.06	0.40	01/07/2016 10:10	15.87	23.9
2016-B	01/07/2016 10:10	15.87	03/07/2016 18:16	15.25	0.62	0	2.34	0.00	21/07/2016 01:40	16.4	17.31
2016-C	27/07/2016 11:15	15.75	28/07/2016 17:00	13.11	2.64	1	1.24	0.00	20/08/2016 08:51	16.33	22.66
2016-D1	20/08/2016 08:51	16.33	23/08/2016 06:00	14.88	1.45	1	2.88	0.00	27/08/2016 12:20	15.73	4.26
2016-D2	27/08/2016 12:20	15.73	30/08/2016 23:20	15.29	0.44	0	3.46	0.00	12/09/2016 14:00	16.88	12.61
2016-E	21/10/2016 00:04	16.55	27/10/2016 11:21	13.37	3.17	1	6.47	0.00	22/11/2016 09:56	17.4	25.94
2017-A1	17/04/2017 18:35	16.39	24/04/2017 02:55	13.54	2.84	1	6.35	0.00	07/05/2017 14:01	15.99	13.46
2017-A2	07/05/2017 14:01	15.99	10/05/2017 16:00	14.68	1.31	0	3.08	0.00	22/06/2017 02:00	16.24	42.42
2017-B1	22/06/2017 02:00	16.24	22/06/2017 19:21	15.81	0.43	1	0.72	0.00	27/06/2017 10:46	16.12	4.64
2017-B2	27/06/2017 10:46	16.12	28/06/2017 10:27	15.26	0.85	0	0.99	0.00	01/07/2017 14:06	15.49	3.15
2017-B3	01/07/2017 14:06	15.49	02/07/2017 23:12	13.90	2.22	9	5.52	4.00	04/07/2017 18:48	14.32	1.82
2017-B4	04/07/2017 18:48	14.32	05/07/2017 18:49	14.01	0.31	1	1.00	0.00	21/07/2017 08:30	16.29	15.57
2017-C1	23/08/2017 08:02	16.01	24/08/2017 05:58	13.97	2.04	1	0.91		26/08/2017 22:48	14.42	2.7
2017-C2	26/08/2017 22:48	14.42	28/08/2017 08:51	12.30	2.12	2	1.42	0.88	03/09/2017 22:36	14.69	6.39
2017-C3	03/09/2017 22:36	14.69	04/09/2017 16:18	13.64	1.05	0	0.74	0.00	21/09/2017 12:10	15.85	16.83
2017-C4	21/09/2017 12:10	15.85	23/09/2017 01:00	15.41	0.44	7	1.53	0.90	30/09/2017 05:04	16.49	7.17
2017-C5	30/09/2017 05:04	16.49	03/10/2017 06:33	15.44	1.05	7	3.06	1.92	09/11/2017 11:58	17.16	37.23
2017-D	09/12/2017 20:24	16.86	12/12/2017 05:12	15.16	1.70	1	2.37	0.00	18/12/2017 19:37	15.89	6.6

Label	Start Date	m_{start}	Peak Date	m_{peak}	Δm	Obs	Max T_{surge}	Min T_{surge}	End Date	m_{end}	T_{decay}
2018/19-A	22/04/2018 19:00	15.82	25/04/2018 19:10	15.32	0.51	0	3.01	0.0	14/06/2018 01:05	16.71	49.25
2018/19-B	14/06/2018 01:05	16.71	23/06/2018 18:56	15.07	1.64	7	9.74	3.17	30/06/2018 19:40	16.70	7.03
2018/19-C	09/07/2018 01:44	16.52	11/07/2018 17:28	16.21	0.32	0	2.66	0.0	30/07/2018 14:21	16.38	20.92
2018/19-D	31/07/2018 06:00	16.31	02/08/2018 01:27	14.58	1.73	2	1.81	0.37	16/08/2018 14:13	16.12	14.53
2018/19-E	16/08/2018 14:13	16.12	20/08/2018 02:48	15.63	0.49	0	3.52	0.0	20/09/2018 09:26	16.17	31.28
2018/19-F1	20/09/2018 09:26	16.17	21/09/2018 10:58	12.99	3.18	1	1.06	0.0	22/09/2018 08:23	13.09	0.89
2018/19-F2	22/09/2018 08:23	13.09	23/09/2018 07:56	12.30	0.79	0	0.98	0.0	05/10/2018 18:08	14.59	12.42
2018/19-F3	05/10/2018 18:08	14.59	13/10/2018 14:06	14.36	0.23	5	7.83	0.2	20/11/2018 00:34	16.49	57.69
2018/19-G1	20/11/2018 00:34	16.49	22/11/2018 02:33	13.49	3.00	0	2.08	0.0	08/12/2018 00:36	16.19	15.92
2018/19-G2	08/12/2018 00:36	16.19	09/12/2018 19:56	14.87	1.32	0	1.81	0.0	13/01/2019 02:11	16.45	34.26
2019/20-A1			13/05/2019 10:23	14.69					08/06/2019 09:04	16.52	25.95
2019/20-A2	08/06/2019 09:04	16.52	11/06/2019 04:31	15.88	0.63	0	2.81	0.0	17/06/2019 02:30	16.62	5.92
2019/20-A3	27/06/2019 00:55	16.58	27/06/2019 02:18	15.26	1.32	0	0.06	0.0	11/07/2019 17:22	16.43	14.63
2019/20-A4	11/07/2019 17:22	16.43	13/07/2019 01:00	16.06	0.37	0	1.32	0.0	20/07/2019 16:10	16.41	7.63
2019/20-A5	20/07/2019 16:10	16.41	24/07/2019 18:07	16.06	0.35	2	4.08	1.06	29/07/2019 17:44	16.24	4.98
2019/20-A6	29/07/2019 17:44	16.24	02/08/2019 16:10	14.69	1.55	3	3.93	1.39	06/08/2019 15:23	15.46	3.97
2019/20-A7	06/08/2019 15:23	15.46	09/08/2019 03:55	15.30	0.16	0	2.52	0.0	11/09/2019 15:11	16.49	33.47
2019/20-B	11/09/2019 15:11	16.49	16/09/2019 12:54	16.05	0.44	4	4.9	2.39	03/10/2019 21:28	16.12	17.36

Label	Start Date	m_{start}	Peak Date	m_{peak}	Δm	Obs	Max T_{surge}	Min T_{surge}	End Date	m_{end}	T_{decay}
2019/20-C	07/10/2019 20:41	15.99	09/10/2019 05:14	15.52	0.47	1	1.36	0.99	15/10/2019 05:14	16.16	6.0
2019/20-D	18/10/2019 21:48	15.99	20/10/2019 03:48	15.30	0.69	0	1.25	0.0	02/11/2019 10:06	16.19	13.26
2019/20-E1	27/11/2019 19:35	16.39	01/12/2019 05:16	15.66	0.73	14	3.4	2.81	05/12/2019 03:20	15.9	3.92
2019/20-E2	05/12/2019 18:35	16.11	06/12/2019 10:10	15.43	0.68	5	0.65	0.15	01/01/2020 06:38	16.85	25.85
2020/21-A			01/08/2020 19:36	14.29					18/08/2020 14:56	16.53	16.81
2020/21-B	23/08/2020 18:03	16.19	24/08/2020 07:15	15.64	0.55	0	0.55	0.0	03/09/2020 03:43	16.27	9.85
2020/21-C1	03/09/2020 03:43	16.27	04/09/2020 01:38	15.52	0.75	1	0.91	0.0	09/09/2020 09:52	16.17	5.34
2020/21-C2	09/09/2020 09:52	16.17	10/09/2020 02:06	15.71	0.46	0	0.68	0.0	27/10/2020 23:22	16.11	47.89
2020/21-D1	19/11/2020 12:05	16.12	19/11/2020 22:44	13.36	2.76	12	0.44	0.13	20/11/2020 03:12	13.51	0.19
2020/21-D2	20/11/2020 03:12	13.51	20/11/2020 08:46	13.31	0.20	4	0.23	0.01	25/11/2020 19:48	15.0	5.88
2020/21-D3	25/11/2020 19:48	15.00	26/11/2020 06:21	14.33	0.67	2	0.44	0.41	14/01/2021 01:18	16.68	48.79
2020/21-E	14/01/2021 01:18	16.68	15/01/2021 05:31	14.94	1.74	6	1.18	0.33	22/02/2021 06:19	17.03	38.03
2021/22-A	04/08/2021 13:48	16.92	10/08/2021 11:08	16.20	0.72	0	5.89	0.0	21/08/2021 03:43	16.85	10.69
2021/22-B1	21/08/2021 03:43	16.85	25/08/2021 12:45	14.56	2.29	1	4.38	0.0	04/09/2021 03:00	15.66	9.59
2021/22-B2	04/09/2021 03:00	15.66	07/09/2021 03:50	15.19	0.47	0	3.03	0.0	25/09/2021 01:15	16.75	17.89
2021/22-C1	25/09/2021 01:15	16.75	28/09/2021 14:44	11.18	5.58	28	3.56	0.56	21/10/2021 14:41	15.34	23.0
2021/22-C2	21/10/2021 14:41	15.34	24/10/2021 11:57	13.26	2.08	0	2.89	0.0	19/11/2021 10:50	16.12	25.95
2021/22-C3	19/11/2021 10:50	16.12	23/11/2021 07:54	15.81	0.31	0	3.88	0.0	01/01/2022 00:00	16.59	38.67

Label	Start Date	m_{start}	Peak Date	m_{peak}	Δm	Obs	Max T_{surge}	Min T_{surge}	End Date	m_{end}	T_{decay}
2021/22-C4	01/01/2022 00:00	16.59	02/01/2022 19:45	16.24	0.34	1	1.82	0.0	14/01/2022 19:25	16.77	11.99
2021/22-C5	14/01/2022 19:25	16.77	16/01/2022 01:54	16.35	0.43	0	1.27	0.0	11/02/2022 07:11	16.68	26.22
2021/22-D1	11/02/2022 07:11	16.68	11/02/2022 21:27	15.24	1.44	0	0.59	0.0	21/02/2022 06:10	16.48	9.36
2021/22-D2	21/02/2022 06:10	16.48	26/02/2022 04:46	16.11	0.36	1	4.94	0.0	12/03/2022 05:21	16.68	14.02
2022/23-A1	17/08/2022 14:45	16.64	19/08/2022 14:45	15.02	1.62	1	2.0	0.0	08/09/2022 14:23	16.27	19.98
2022/23-A2	08/09/2022 14:23	16.27	10/09/2022 14:21	15.13	1.14	0	2.0	0.0	11/10/2022 14:31	16.45	31.01
2022/23-B	11/10/2022 14:31	16.45	17/10/2022 11:41	15.40	1.05	0	5.88	0.0	02/11/2022 15:25	16.57	16.16
2022/23-C1	16/11/2022 14:06	16.68	23/11/2022 10:01	12.21	4.47	4	6.83	0.29	27/11/2022 09:10	13.38	3.96
2022/23-C2	27/11/2022 09:10	13.38	28/11/2022 08:14	12.16	1.22	8	0.96	0.24	23/12/2022 00:53	15.94	24.69
2022/23-C3	23/12/2022 00:53	15.94	28/12/2022 03:18	14.42	1.51	0	5.10	0.0	11/01/2023 06:15	15.9	14.12
2022/23-C4	11/01/2023 06:15	15.90	13/01/2023 20:49	15.12	0.78	4	2.61	1.98	29/01/2023 01:55	16.52	15.21
2022/23-D	29/01/2023 01:55	16.52	30/01/2023 02:11	15.39	1.13	0	1.01	0.0	16/02/2023 02:08	16.66	17.0
2022/23-E	20/02/2023 11:42	16.62	23/02/2023 02:34	14.61	2.00	2	2.62	0.04	20/03/2023 20:08	16.76	25.73
2022/23-F	20/03/2023 20:08	16.76	24/03/2023 02:51	15.24	1.52	2	3.28	1.0	01/04/2023 05:36	17.01	8.11
2022/23-G	01/04/2023 05:36	17.01	03/04/2023 09:18	15.26	1.75	6	2.15	1.14	26/04/2023 21:29	16.7	23.51
2022/23-H	26/04/2023 21:29	16.70	28/04/2023 20:33	16.23	0.48	0	1.96	0.0	04/05/2023 21:07	16.72	6.02
2023/24-A1	07/12/2023 08:34	16.67	11/12/2023 00:58	13.25	3.42	6	3.68	3.32	14/12/2023 00:02	13.95	2.96
2023/24-A2	14/01/2024 16:13	15.93	15/12/2023 01:05	13.07	2.86				22/12/2023 17:02	15.18	7.66

Label	Start Date	m_{start}	Peak Date	m_{peak}	Δm	Obs	Max T_{surge}	Min T_{surge}	End Date	m_{end}	T_{decay}
2023/24-A3	22/12/2023 17:02	15.18	24/12/2023 15:44	14.14	1.04	0	1.95	0.0	30/12/2023 05:00	15.72	5.55
2023/24-A4	02/01/2024 22:45	15.18	04/01/2024 10:40	14.84	0.34	0	1.5	0.0	13/01/2024 00:00	15.65	8.56
2023/24-A5	13/01/2024 00:00	15.65	19/01/2024 00:59	14.15	1.50	2	6.04	0.0	05/02/2024 06:57	16.15	17.4
2023/24-A6	05/02/2024 06:57	16.15	06/02/2024 22:50	15.45	0.69	0	1.66	0.0	11/02/2024 07:30	16.12	4.36
2023/24-A7	11/02/2024 07:30	16.12	13/02/2024 12:59	14.83	1.29	0	2.23	0.0	25/02/2024 04:00	16.33	11.63
2023/24-A8	25/02/2024 04:00	16.33	25/02/2024 19:54	15.93	0.40	0	0.66	0.0	08/03/2024 20:43	16.62	12.03
2023/24-B	08/03/2024 20:43	16.62	09/03/2024 00:45	15.19	1.43	3	0.17	0.01	23/03/2024 04:58	16.57	14.18
2023/24-C	23/03/2024 04:58	16.57	25/03/2024 06:45	13.91	2.66	5	2.07	0.27	20/04/2024 06:52	16.61	26.0
2023/24-D1	20/04/2024 06:52	16.61	21/04/2024 07:24	15.21	1.40	1	1.02	0.0	04/05/2024 03:20	16.22	12.83
2023/24-D2	04/05/2024 03:20	16.22	11/05/2024 23:48	15.69	0.52	1	7.85	0.0	22/05/2024 16:39	16.66	10.7
2024/25-A1	22/10/2024 14:00	17.01	24/10/2024 02:45	16.40	0.61	0	1.53	0.0	01/11/2024 02:15	16.79	7.98
2024/25-A2	01/11/2024 02:15	16.79	04/11/2024 15:32	12.22	4.57	2	3.55	0.33	09/11/2024 13:11	13.69	4.9
2024/25-A3	09/11/2024 13:11	13.69	09/11/2024 13:32	13.24	0.45	0	0.01	0.0	20/11/2024 12:24	15.16	10.95
2024/25-A4	20/11/2024 12:24	15.16	23/11/2024 17:36	12.82	2.34	0	3.22	0.0	24/11/2024 12:01	12.87	0.77
2024/25-A5	24/11/2024 12:01	12.87	24/11/2024 17:06	12.64	0.23	0	0.21	0.0			
2024/25-B1	25/12/2024 15:09	16.61	27/12/2024 17:09	16.12	0.49	2	2.08	0.14	02/01/2025 10:11	16.48	5.71
2024/25-B2	02/01/2025 10:11	16.48	03/01/2025 00:30	14.43	2.05	0	0.6	0.0	06/01/2025 09:47	15.4	3.39
2024/25-B3	06/01/2025 09:47	15.40	07/01/2025 09:46	13.65	1.74	1	1.0	0.0	15/01/2025 09:50	15.65	8.0

Label	Start Date	m_{start}	Peak Date	m_{peak}	Δm	Obs	Max T_{surge}	Min T_{surge}	End Date	m_{end}	T_{decay}
2024/25-B4	15/01/2025 09:50	15.65	19/01/2025 04:19	14.41	1.24	6	3.77	2.24	21/01/2025 10:35	14.76	2.26
2024/25-B5	21/01/2025 10:35	14.76	21/01/2025 23:58	14.24	0.52	0	0.56	0.0	31/01/2025 10:50	15.37	9.45
2024/25-B6	31/01/2025 10:50	15.37	03/02/2025 02:48	12.56	2.80	4	2.67	0.64	19/02/2025 09:53	15.16	16.29
2024/25-B7	15/03/2025 09:39	16.04	16/03/2025 23:54	15.48	0.56	0	1.59	0.0	21/03/2025 12:12	15.9	4.51
2024/25-B8	21/03/2025 12:12	15.90	23/03/2025 00:05	15.35	0.55	1	1.5	0.0	10/04/2025 11:29	16.89	18.48
2024/25-C1	12/05/2025 16:57	16.83	14/05/2025 00:08	13.85	2.98	1	1.3	0.0	24/05/2025 10:49	15.86	10.45
2024/25-C2	24/05/2025 10:49	15.86	26/05/2025 03:55	14.31	1.55	1	1.71	0.0	02/06/2025 22:59	15.73	7.79
2024/25-C3	02/06/2025 22:59	15.73	04/06/2025 16:40	15.03	0.70	0	1.74	0.0	23/07/2025 08:22	17.14	48.65

TABLE J.1: Outburst Events Summary

Appendix K

Decay Fit Attempts

Investigation was conducted to estimate the best approximation for the decay curve following an outburst. Numerous equations (equations [K.1](#) to [K.5](#)), were trialled and using the MSE, it was possible to select the best equation to approximate the Centaur's decay in brightness. Fitting curves to the data was conducted using SciPy's `curve_fit` function, using the following equations as the model function. The MSE was calculated using equation [8.2](#).

$$f(t) = at^2 + bt + c \quad (\text{K.1})$$

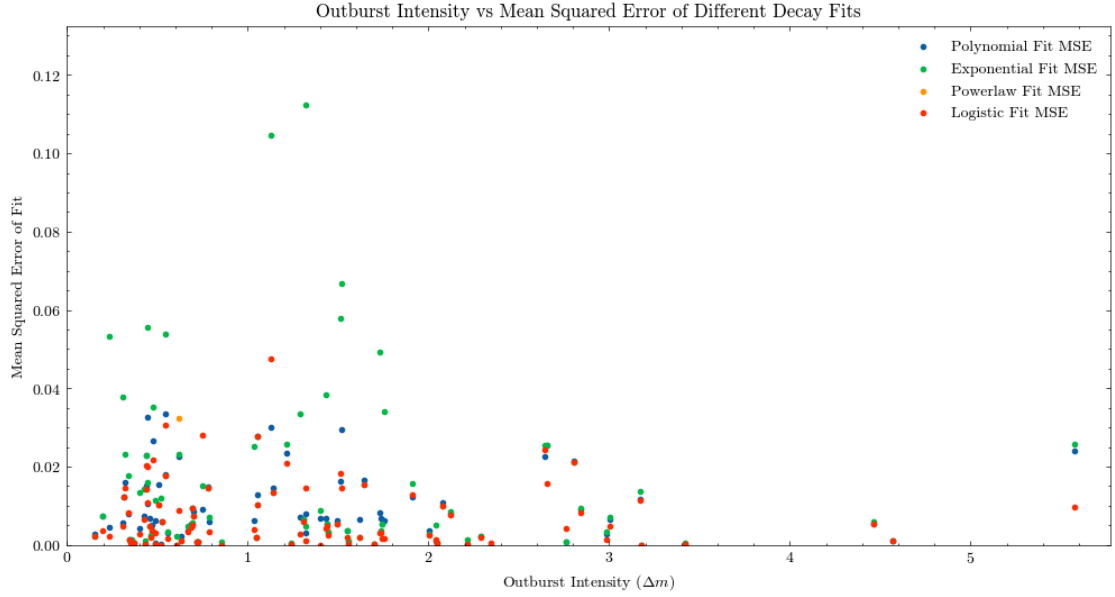
$$f(t) = at^3 + bt^2 + ct + d \quad (\text{K.2})$$

$$f(t) = ae^{bt} \quad (\text{K.3})$$

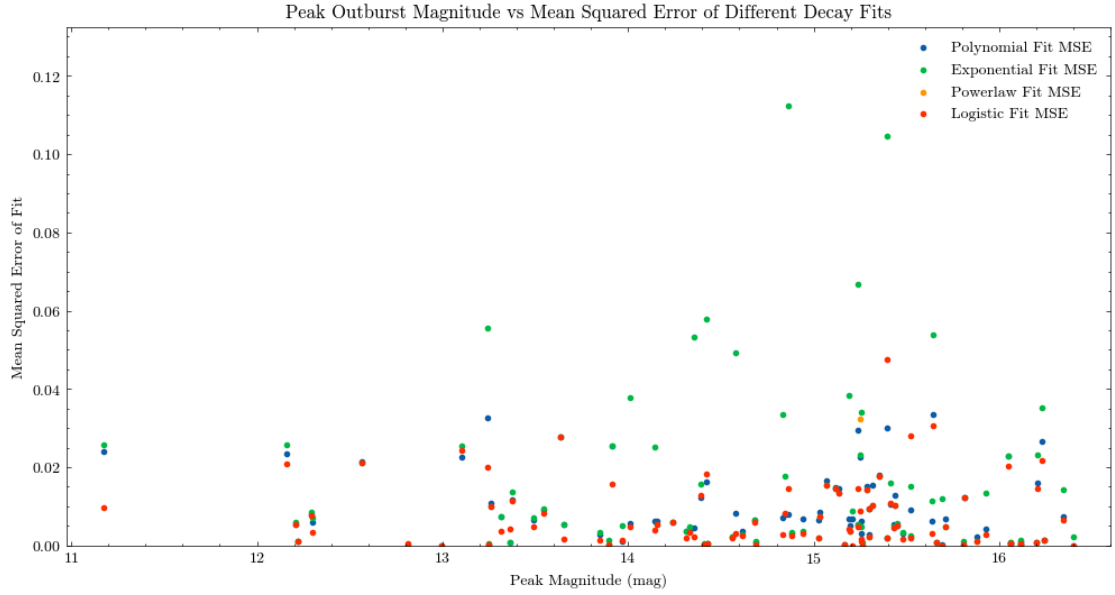
$$f(t) = t_0 + 2.5\alpha \log t \quad (\text{K.4})$$

$$f(t) = \frac{A}{1 + e^{-k(t-t_0)}} + \text{offset} \quad (\text{K.5})$$

By taking the mean of the MSE for each different fit, it is possible to assess which fit best approximates the brightness decay curve following an outburst. Table [K.1](#) summarises these values. The cubic equation (eq. [K.2](#)) fitted the data the best, closely followed by the logistic equation (eq. [K.5](#)). To best fit the data using the exponential function, the data had to be limited to $t_{epoch} \leq 20$ days,



(A) MSE distribution based on an outburst's surge in magnitude.



(B) MSE distribution based on an outburst's peak magnitude.

FIGURE K.1: Comparisons of MSE of each fit used to approximate the decay curve seen following an outburst. Equations used with SciPy's curve_fit function are presented in equations K.1 to K.5.

otherwise the MSE exceeded 10^{13} . Regardless, using this function did not fit the dataset as well as the logistic or quadratic functions. Using the power-law equation (equation K.4) the function failed to resolve a fit.

There are benefits to using either the cubic or logistic fits. The cubic equation fits the data set better, giving a lower MSE for all outbursts analysed, while the

TABLE K.1: Summary of fits used and mean squared error.

Fit	Equation	MSE ($\times 10^{-3}$)
Quadratic	K.1	11.02 ± 10.85
Cubic	K.2	7.31 ± 7.34
Exponential	K.3	14.98 ± 20.26
Power-Law	K.4	N/A
Logistic	K.5	8.99 ± 9.64

logistic fit accounts for the plateau in brightness when the magnitude returns to a roughly normal nuclear level. Cubic fit begins to fail ~ 20 days following an outburst, additional data after this period increases the MSE. Numerous cubic fits end with a negative gradient, suggesting an increase in brightness. We treat the maxima of this curve to represent the end of the decay period.

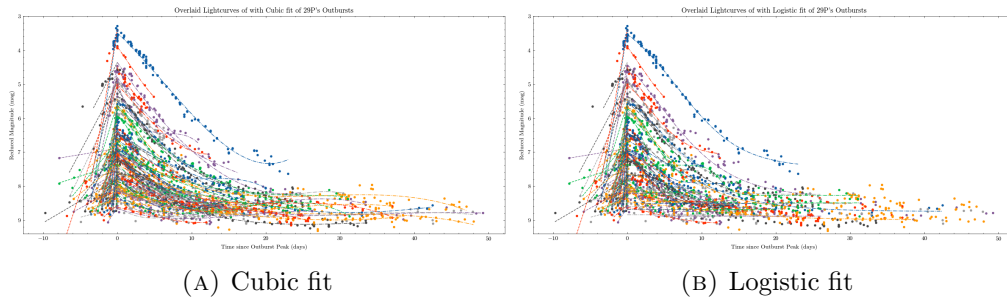


FIGURE K.2: Fits of decay period using different functions.

When calculating the maxima position for these curves, values occurring with maxima positions at $t < 0.2$ and $t > 29.9$ were eliminated, along with any maxima magnitude value greater than 10 mag. This criteria was set as it displays that the fit of these is inadequate. The 'normal' nuclear magnitude is never > 10 mag, and maxima times at the start and end of the period searched also indicate that the fit is poor.

Appendix L

SDSS to Johnson-Cousins Filter Conversion

Given images were observed using SDSS filters, colour values should be converted into BVR filters to compare the calculated results with those found in literature. Jester et al. 2005 provides conversions from $g-r$ to $B-V$ and $r-i$ to $V-R$, see equations L.1 and L.2. It is important to note that these conversions are for stars, not comets/centaurs, therefore discrepancies may exist, especially during periods when the object appears diffuse following an outburst.

$$B - V = 0.98(g - r) + 0.22 \quad (\text{L.1})$$

$$V - R = 1.09(r - i) + 0.22 \quad (\text{L.2})$$

Notice that the SDSS colours here are not the prime versions used in our observations, these are known as SDSS 2.5m ugriz system, slightly different from the SDSS u'g'r'i'z' system due to variations in the effective wavelengths between telescopes used to conduct the SDSS survey.

Unprimed magnitudes can be calculated from their primed counterpart via equations L.3, L.4, and L.5 (SDSS 2005).

$$g(2.5m) = g' + 0.060((g' - r') - 0.53) \quad (\text{L.3})$$

$$r(2.5m) = r' + 0.035((r' - i') - 0.21) \quad (\text{L.4})$$

$$i(2.5m) = i' + 0.041((r' - i') - 0.21) \quad (\text{L.5})$$

The primed colour indices can be calculated by subtracting two of the above equations. Note that $g - r$ is dependent on both indices $g' - r'$ and $r' - i'$.

$$(g - r)_{2.5m} = 1.060(g' - r') - 0.035(r' - i') - 0.039 \quad (\text{L.6})$$

$$(r - i)_{2.5m} = 0.994(r' - i') - 0.016 \quad (\text{L.7})$$

Substituting these conversions into equations [L.1](#) and [L.2](#) gives,

$$B - V = 1.039(g' - r') - 0.034(r' - i') + 0.182 \quad (\text{L.8})$$

$$V - R = 1.083(r' - i') + 0.203 \quad (\text{L.9})$$