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Perspective

Astronomical measurements 1923–2023: a century of astonishing progress

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Abstract

How have advances in technology changed astronomy over the past 100 years? In this very brief review I will give examples of just how closely discovery has followed technical innovation, allowing observations that would previously have seemed impossible. Obviously great progress has come from spaceflight allowing observations from outside the Earth's atmosphere. But two other factors have also been crucial—the development of efficient detectors of electromagnetic radiation and the application of computers to both instrument control and data analysis. Driving down experimental errors in pursuit of ever-more accurate measurements has been important too. I will particularly highlight advances in cosmology, the nature of galactic nuclei and the discovery of exoplanets.

Keywords: astronomical, measurements, century, progressing, technology

(Some figures may appear in colour only in the online journal)

1. Introduction

In 1923 the scientific world was still absorbing the results [1] of the 1919 eclipse expedition. It had been shown that the deviation of stellar images by the mass of the Sun was in better accord with General Relativity than Newtonian gravity. The results were rather marginal. Sir Frank Dyson had been the prime mover in the expedition, and was the Astronomer-Royal and a past-President of the Royal Astronomical Society. This year he was publishing [2] a short paper in the Journal of Scientific Instruments—the predecessor of Measurement Science and Technology—suggesting improvements in how the all-important calibration of the stellar positional measurements might be achieved. The ensuing century presents a fascinating tale of an explosion of astronomical knowledge. In hindsight it is obvious how completely this advance was tied to the technological advances made in experimental and observational capability. In this article we will only have space to review progress in just a few astronomical research areas, and we can only acknowledge (rather than catalogue) the considerable social and economic benefits that technology transfer or co-development has allowed. For an excellent overview of astronomy in the twentieth we would recommend Longair's Cosmic century [3].

Before 1923 virtually all our knowledge of the heavens had been derived from observations at visible wavelengths. There existed neither the transparency of the atmosphere at other wavelengths nor indeed the detection technology to allow investigation at radio, infrared, ultraviolet, x-ray and gamma ray wavelengths. Following some early experiments [4] in the 1930s, the radio wavelengths became accessible from the ground after rapid technological advancements during the Second World War. But the other wavelengths could only be tackled once rockets and satellites took telescopes above the Earth's turbulent and absorbing atmosphere. In most of these areas it was not just a matter of improved instrumentation or accuracy, but the possibility of observation at all. Some atmospheric windows exist in the near-infrared, but here lack of suitable detectors held back major astronomical development until the 1960s.

Three general areas of fundamental technological advance need to be noted. Application of at least two of these three areas will be evident in each astronomical breakthrough we will consider (i) the development of detectors (ii) the development of spaceflight (iii) the development of computer control and data handling for both instruments and telescopes. Of course, spaceflight has also allowed the close examination of our own planetary system giving—from around 1960—images and physical measurements which would have seemed an impossible dream in the 1920s. Ground-based radio observations gave us quasars [5] and pulsars [6] in the 1960s. Space-based x-ray observations indicated high energy interactions in some binary star systems, which combined with optical spectroscopy [7] showed the existence of stellar-mass black holes in the 1970s. Infra-red observations penetrated the obscuring interstellar dust into regions of active star formation and into the nuclear regions of galaxies, revealing the massive black holes hidden there with their accompanying hot accretion discs.

2. Telescopes and detectors

The size of ground-based telescopes has increased only slowly. In 1923 the largest instrument was the Mt Wilson 100′′ reflector—the size (2.5 m) referring to the primary mirror diameter. By 1949 the Palomar 200′′ (5 m) was available, a light collecting area increase of a factor of four. Several modern and very productive telescopes of slightly *smaller* size were opened in the 1970s, but nothing much larger was available until the first of two 10 m Keck telescopes started operation in 1993. A *significant*ly larger aperture of 39.3 m—a massive jump of 15x in area from the Kecks—will only be achieved [8] in 2027 with the ESO 'Extremely Large Telescope'. So from 1923 to 2023 there has only been a factor 16 increase in the collecting area of the largest telescope, but nevertheless a revolution in observing power has come about because of the radical improvement in radiation detection and cleverly-designed instrumentation to exploit these new detectors. In 1923 optical radiation detection was basically limited to photographic emulsions (typically perhaps 2% efficient), some fairly primitive single-channel photoelectric photometers, and the human eye. There are legendary rumours of tired astronomers carefully exposing a photographic plate over several nights to reach faint objects, only to mistakenly develop it in the fixer! Specialised photographic emulsions could reach some 4% efficiency over a limited wavelength range but suffered from non-linear response requiring careful calibration. Yet photography remained a valuable technique for direct imaging of the sky over most of our period because of the vast storage area available on a single plate. For quantitative spectroscopy a breakthrough occurred by the use of a photocathode to convert the photons to electrons, which were then accelerated and/or multiplied before direct detection or conversion to an optical signal by a phosphor observed by a TV system. The immediate advantages were the much higher quantum efficiency, and the possibility of real-time readout of the detections allowing efficient control of exposure times. Problems did remain—such as some non-linearity of response and saturation, but the overall efficiency (approaching tens of %) was much greater the photographic plate. Three examples of very successful composite systems from 1970s and 1980s were the image-dissector scanner [9], the Intensified Reticon scanner [10] and the Image Photon Counting System [11].

The silicon-chip CCD (charge coupled device) invented [12] in 1969 was first intended for computer memory, but it was soon realised that it made an excellent optical light detector if thinned and used in particular configurations. Its structural rigidity, compactness and (when developed) large area were soon exploited in both astronomical imaging and spectroscopy, and by the mid-1980s it had become the detector [13] of choice in most applications. Commercial development led to its almost universal use in digital cameras and mobile phones. Its astronomical use in faint object detection is enhanced by clever readout to minimise noise, reaching at peak almost-perfect (perhaps 80%) conversion of photons into electrical signals. It will be noted that successful imaging systems since the photographic plates have relied very heavily on co-development of electronics and computation. The large *area* of detectors has been exploited for spectroscopy since the early 1980s by techniques such as using multiple entrance slits or optic fibres [14] (developed for the communications industry) to feed light simultaneously from many objects through the spectrograph and onto a single chip—or array of chips. By 1997 the Anglo-Australian 3.9 m telescope had a 400-fible automatic positioner operating over a 2-degree field on the sky [15]. The gain for spectroscopy of faint objects from 1923 to the present by improved detection and associated spectrograph design must be of order a 1000, of which—as we have noted—only a factor of 16 is due to increased telescope aperture. In the late 1960s or early 1970s the average astronomer would never have expected that the spectrum of a normal galaxy could be observed above a redshift of one. That artificial limit was broken [16] (for a particularly active galaxy) in 1982 and the James Webb Space Telescope is now reported [17] as confirming galaxy redshifts around 12, and hence beginning to reach directly into the era of the formation of the very first galaxies.

3. Observational cosmology

The rewards of achieving spectroscopy of ever-fainter objects are particularly notable in cosmological studies. The first measurement of the radial velocity (i.e. line-of-sight Doppler motion away or towards us) of a galaxy had been made only ten years [18] before 1923. In 1929 Edwin Hubble published [19]

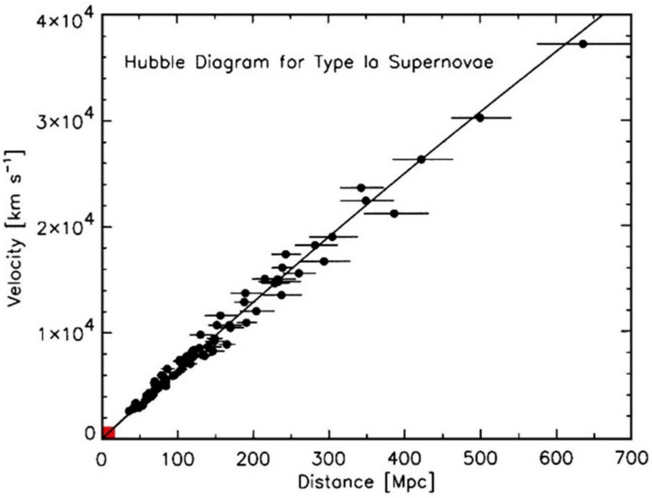

Figure 1. An example of the diagram by 2002 out to redshift 0.12. The region of Hubble's original plot is shown as the small red rectangle in the bottom left. Extensions to higher redshifts ($z \sim 1$) show significant deviations from a linear relationship. Reproduced with permission from [20]. Copyright (2003) National Academy of Sciences, U.S.A.

a diagram (see figure 1) which ostensibly showed that the velocities of recession—the 'redshifts'—of galaxies (as measured in their visible spectra) bear a linear relation to their distance away. In retrospect the magnitude of the errors in this diagram would discourage even a second-year physics student from handing in their work, but subsequent accumulation of data has amply demonstrated [20] the correctness (see figure 1) of Hubble's conclusion. Its implication—the expansion of space in the Universe—is profound. Because of many technical difficulties in establishing accurate distance scales, the actual rate of expansion was argued over, so that by the early 1990s there was still a factor of two uncertainty. There had been a period of uncertainty in the 1950 and early 1960s over the interpretation of the expansion, but a 'Steady State' model had to yield to an evolving Universe starting with a 'Big Bang' once a proper (evolutionary) interpretation of the relative numbers of distant radio sources had been sorted out, and because of the serendipitous 1964 discovery [21] of the background radiation left over from the early hot stages of the expansion. This now-cooled '3 degree' radiation could perhaps be viewed as the greatest ever cosmological discovery, not merely because of its direct confirmation of the occurrence of the Big Bang—it is virtually impossible to explain its properties in any other way—but also because the subsequent detailed study of the properties of the radiation so closely constrain cosmological parameters. Initial refinement of the determination of the temperature showed an isotropic nearly-perfect black-body spectrum. The cosmic background explorer (1989–1993) satellite observed in the microwave and far-infrared radiation and detected tiny temperature fluctuations in this smooth background. The variations at a level of 3 (±0.5) × 10^{-5} immediately implied [22] fluctuations in density in the early universe of a size that would have subsequently led to large-scale structure and the formation of galaxies. The Planck satellite (2009–2013) was able to investigate with precision [23] the correlation of temperature fluctuations as a function of angular distance on the sky—a data-processing-intensive task. This angular spectrum places very stringent and significant limits on the parameters of cosmological models. While these background radiation studies were progressing another crucial advance came from the pushing of the observation of the Hubble expansion to galaxies at higher redshift. This was possible in part because of the availability of the efficient detectors already mentioned, but also through [24] the rapid identification and observation of Type Ia supernova that could be used as a reasonably reliable distance indicator. The results even at moderate redshift ($z \sim 0.4$–0.8 in this context) show that the expansion is beginning to *accelerate*, widely interpreted as implying the existence of a 'dark' energy. This is consistent with the observed details of the background radiation. Measurement of the rotation of galaxies and the dynamics of clusters of galaxies, again enabled by modern spectroscopic capability, has shown [25] the gravitational effect of a significant 'dark' matter component too. We have reached a position where the measurement of many cosmological parameters, for example the age of the Universe 13.81 ± 0.05 years, and its geometry—*flat*, have been firmly established. This is marvellous progress since 1923. *BUT* since we have as yet essentially no idea of the nature of the dark matter and dark energy that dominate the expansion and geometry of the Universe it would be foolish to think that cosmology has been sorted out! There is a widely held opinion that some breakthrough in fundamental physics may be needed if further significant progress in explanation or understanding is to be achieved, rather than just measurement (albeit a remarkably precise one) of its fundamental structure. There is some ongoing tension [26] between the slightly varying results of different methods of measuring the rate of Hubble expansion which may either resolve into agreement or perhaps be a pointer to that new physics.

4. Positional astronomy: the blossoming of tradition

One of the very basic aspects of observational astronomy has been the measurement of the positions [27] of stars in the sky. They have probably been measured as far back as prehistoric times, and certainly by the ancient Greeks. Detection of a regular shift in position—the parallax—due to the Earth's orbital motion around the Sun allows an estimate of the distance of the star. The problem is that under normal atmospheric conditions the apparent image of a star viewed from the ground is some 1–2 arcseconds in diameter, while even the closest star is far enough away to have a parallax of less than 1 arcsecond. The first reliable detection of such shifts was not published until 1838, and by [28] January 1924 the use of photographic techniques had resulted in parallax (and hence distance) measurements of very variable quality for some 1700 stars. A parallax of one second of arc serves to define an astronomical distance of one parsec (3.1 × 10^{16} m). With a typical error no better that 0.01″ this implies distances could only be estimated out to 50 parsecs. By 1988 the sample had risen [29] to around 3800 stars with reasonably reliable distance determination, but still limited to 50 pc—a tiny fraction of the size of even our own Galaxy, with the Earth 8.2 *kilo* parsecs away from the centre. The major problem remained of the limiting of the parallax measurements by the smearing effect of the atmosphere on the stellar images. Two satellite missions have radically improved matters—Hipparcos [30] launched in 1989 and operational until 1993, and the ongoing GAIA [31] launched in 2013. The operational principle of the GAIA satellite is gloriously simple. As the spacecraft rotates, star images drift across focal-plane CCD detectors [32] looking at two areas of sky which are at a large angle to each other. Systematic scanning over the sky and accurate *timing* of the track of the star images across the detectors allows the extraction of very accurate relative celestial positions (and their change with time) from intensive data processing. The third release of GAIA data [33] in 2022 covers almost 1.5 *billion* sources and achieves a minimum error 10 *micro* arcseconds, with somewhat lower accuracy of 500 µ arcsec for the faintest measurable sources. The distance estimate limit implied by a typical 100 µ arcsec error is 10 kpc—i.e. 200 times further than in 1924, and encompassing around a million times more stars. These stellar positions also allow a leap in the quality and quantity of the measurements of 'proper motions'—the systematic drifts across the sky with time due to the stars' tangential motions relative to the Sun. Combined with radial velocity measurements the *three-dimensional* motion of the star can be determined, in the case of Gaia providing dynamical information across half the Galaxy—which will be invaluable in sorting out the 'archaeology' of its formation and evolution.

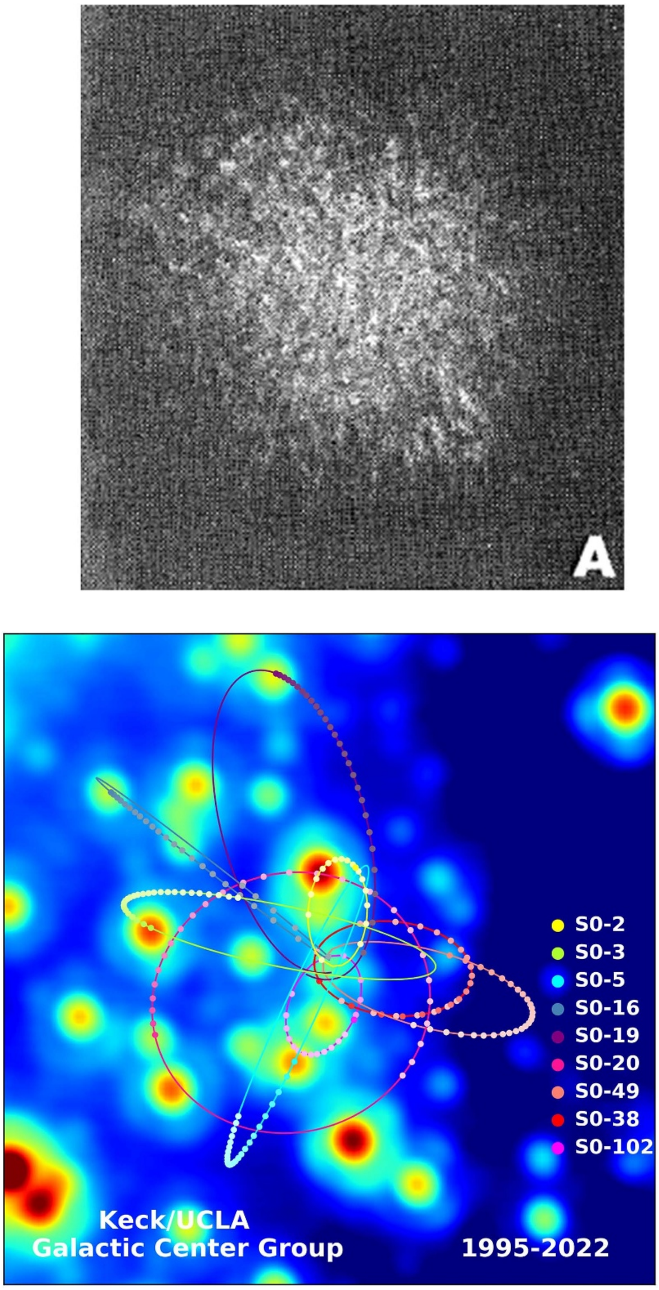

Figure 2. (A) A short-exposure (0.01 s) image of a single star as seen through a 4 m telescope, at optical wavelengths showing its 'speckled' structure due to atmospheric turbulence. Longer exposure will blur the image into a quasi-Gaussian 'seeing' disc. The field of view here is 3 × 3 arcseconds. Reprinted with permission from [49] © The Optical Society. (B) The annual positions of stars at the centre of our Galaxy, plotted as dots, based on adaptive optics images from the Keck telescopes. It shows fitted orbital ellipses. The star SO2 has been followed through a complete 16 year orbit. The field of view here is 1 × 1 arcsecond. Copyright of the UCLA Galactic Centre Group—W.M. Keck Observatory Laser Team.

5. Extraordinary imaging and the galactic centre

Although, as mentioned previously, images at visible wavelengths are blurred by atmospheric turbulence, the effects are less serious in the infra-red, and novel techniques can process the turbulent image—so called 'speckle interferometry'—to extract spatial information on scales way below the overall size of the blurred image. The technique relies on good infrared array detectors not readily available until around end of the 20th century. Even more impressive is the development over the past 30 years of *adaptive optics* [34] (AO) in which wavefront perturbations caused by the atmosphere are corrected in real time by the simultaneous observation of an artificial spot of light generated by a laser stimulating a layer of sodium atoms at about 90 km up in the atmosphere. Rapid-timescale analysis of the artificial image allows correction of the wavefront by a deformable mirror in the telescope imaging optics. Here of course laser technology, as well as rapid image detection and analysis, were necessary prerequisites—and made much more practical (reduced power requirements and improved reliability) since 2015 by the use of Raman-fibre amplification lasers [35]. A fine example of the development and exploitation of both these ground-based observational techniques (speckle and AO) is a programme lasting over 25 years by both US and European teams. It has enabled the reconstruction of infrared (2.2 µm) images of the very central regions of our Galaxy that follow the moving stellar positions with an accuracy of a few milli-arcseconds (See figure 2). It has been possible to see a complete 16 year elliptical orbit [36] of one of the stars about the centre, elementary dynamics then clearly demonstrating that there is a black hole of $4.6 \pm 0.6 \times 10^6$ solar masses lurking there. The observational feat is extraordinary when it is realised that the size of the whole beautifully-traced orbit as observed from earth is small compared to the typical atmospherically-blurred disc of a star viewed through a large telescope. Use of AO has also allowed spectrographic radial velocity measurements [37] of the star, which near pericentre is moving at 2.5% of the speed of light, and clearly show expected special and general relativistic effects—Newtonian dynamics are not enough!

6. Exoplanets

Spectroscopic measurements of the radial velocity of stars were certainly being made in 1923, and by 1948 the radial velocity of a bright star [38] by repeated observations could be measured to an accuracy of 0.2 km s^{-1}. A single measurement would not be better than ±1 km s^{-1}, which is adequate for the elementary study of stellar kinematics and the dynamics of binary systems or clusters of stars. The Sun was a special case, given the abundance of its light and the possibilities of spatially resolving individual surface areas, and observational helioseismology began in 1960 with the discovery [39] of five-minute oscillations with amplitude at the 1 km s^{-1} level. With better detectors the study later broadened out to observations of bright stars, creating the whole field of stellar seismology [40] and its implications for the internal structure of stars. The drive to higher accuracy in radial velocity measurement also had another aspect. The possibility that stars other than the Sun had planetary systems had been approached by looking [41] for 'wiggles' in the transverse (or 'proper') motion of nearby stars across the sky, caused by the star orbiting the centre of mass of the putative planetary system. The displacements would indeed have been very small, and detection claims in the 1960s were regarded with suspicion, and subsequently discounted. But improvements [42] came in radial velocity measurements both through better control of spectrograph stability (especially temperature) and improved reference spectra. In particular, passing the light from the star through a cell filled with iodine vapour could impose a stable reference spectrum in region ~500–610 nm. More recently laser-generated spectral 'combs' have been used, and accuracies of order 1 m s^{-1} achieved. By 1995 an accuracy of order 15 m s^{-1} was sufficient to discover [43] a Jupiter-mass planet by the periodic change in the radial velocity of the star 51 Pegasi. Although not the very first extra-solar planet to be discovered—a system discovered through pulsar timing [44] slightly pre-dates it—its radial velocity method heralded a golden age of 25 years of exoplanet discovery. Other methods, such as looking for the very slight eclipse of the star by a planet, have also been very successful, but the spectroscopic method is particularly valuable in providing fairly direct information on the planetary masses. This is still a young field of investigation, but by January 2023 approximately 5250 planets are known [45] in 3900 systems, and—most delightfully—the properties of these systems are *nothing like* what was expected before their discovery, and most are very different from our Solar System.

7. Gravitational waves

In terms of sheer technical achievement, one can only be in awe of the direct detection of gravitational waves, reported [46] exactly 100 years after the publication of their prediction by Einstein in 1916. Observation involved long-baseline (4 km) modified-Michelson interferometers using Nd:YAG lasers, essentially monitoring the relative separation of test masses placed 4 km apart at the ends of the interferometer arms. Such 'observatories' were first proposed in the 1970s, developed into concrete proposals by 1989, and built in their successful form by 2015. The interferometers require extreme seismic vibration isolation, novel resonant cavities and light recycling, large vacuum systems (to a pressure of 1 micro Pascal to reduce optical scattering) and clever data processing to dig a tiny—but characteristic—signal out of noise. The relative disturbance hL in length L of the arms measured as the gravitation wave passed is characterised as the *strain* h, where h is 1×10^{-21}. With L as 4 km, the implied phase disturbance in the interferometer is equivalent to a physical disturbance of 4×10^{-18} m, i.e. the oft-quoted and astonishing figure of measuring one-hundredth of the diameter of a nucleus. The first detection was the 'chirp' signal lasting some one-fifth of a second from the merger of a binary system of two black holes, combining into a single black hole of 62 ± 4 solar masses, and in the process radiating the equivalent of three solar masses as energy in gravitational waves. No significant deviation from the theoretical predictions of General Relativity were found. This is a new astronomy for the rest of the 21st century, certainly leading not only to better understanding of violent events involving neutron stars and black holes, but also major cosmological implications if gravitational waves can be identified from the very early Universe.

The existence of gravitational waves was actually no longer in doubt after their ingenious *indirect* detection some 37 years earlier in 1979. The 1975 discovery [47] of a binary star system involving a pulsar (rotating neutron star) provided a laboratory in which the orbital dynamics of the system could be studied with the pulsed radio emission providing an intrinsic moving and very regular 'clock'. Availability of Earth-based atomic time reference with errors not exceeding 10 micro seconds allowed extremely accurate timing and analysis of the arrival of the pulses at Earth over an extended period. It was possible to see both the precession of the periastron of the elliptical orbit (at a rate which is 35 000 times that predicted from General Relativity for the planet Mercury's orbit around the Sun!), and to match exactly the slow decay of the orbit by the expected radiation of gravitational waves [48]. The masses of the two binary components can also be inferred to what is exquisite accuracy for an astronomical system: 1.4398 ± 0.0002 and 1.3886 ± 0.0002 solar masses.

8. Conclusion

I have not even mentioned the Hubble Space Telescope, the Event Horizon Telescope and many, many other topics. I have sketched only a few areas, in several of which the progress has deservedly led to Nobel prizes. But this should be ample illustration of the power of new technologies and ever-increasing precision of measurement to unlock access to the mysteries of the heavens. It was a wonderful 100 years for discovery, especially since 1950. The next century beckons!

Data availability statement

No new data were created or analysed in this study.

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