The Astrophysics of Planetary Systems: Formation, Structure, and Dynamical Evolution
Proceedings IAU Symposium No. 276, 2010
A. Sozzetti, M. G. Lattanzi & A. P. Boss, eds.

doi:10.1017/S1743921311020448

The science of EChO

Giovanna Tinetti[1] (*UCL*), James Y-K. Cho (*QMUL*), Caitlin A. Griffith (*UoA*), Olivier Grasset (*Un. Nantes*), Lee Grenfell (*DLR*), Tristan Guillot (*Obs. Nice*), Tommi T. Koskinen (*UoA*), Julianne I. Moses (*SSI*), David Pinfield (*UH*), Jonathan Tennyson (*UCL*), Marcell Tessenyi (*UCL*), Robin Wordsworth (*LMD*) **and**
Alan Aylward (*UCL*), Roy van Boekel (*MPIA*), Angioletta Coradini (*INAF/IFSI Roma*), Therese Encrenaz (*LESIA, Obs. Paris*), Ignas Snellen (*Un. Leiden*), Maria R. Zapatero-Osorio (*CAB*) **and**
Jeroen Bouwman (*MPIA*), Vincent Coudé du Foresto (*LESIA, Obs. Paris*), Mercedes Lopez-Morales (*IEEC*), Ingo Mueller-Wodarg (*Imperial College*), Enric Pallé (*IAC*), Franck Selsis (*Un. Bordeaux*), Alessandro Sozzetti (*INAF/OATo*) **and**
Jean-Philippe Beaulieu (*IAP*), Thomas Henning (*MPIA*), Michael Meyer (*ETH*), Giuseppina Micela (*INAF/OAPa*), Ignasi Ribas (*(IEEC)*, Daphne Stam (*SRON*), Mark Swain (*JPL*) **and**
Oliver Krause (*MPIA*), Marc Ollivier (*IAS*), Emanuele Pace (*Un. Firenze*), Bruce Swinyard (*UCL*) **and**
Peter A.R. Ade (*Cardiff*), Nick Achilleos (*UCL*), Alberto Adriani (*INAF/IFSI Roma*), Craig B. Agnor (*QMUL*), Cristina Afonso (*MPIA*), Carlos Allende Prieto (*IAC*), Gaspar Bakos (*CfA*), Robert J. Barber (*UCL*), Michael Barlow (*UCL*), Peter Bernath (*Un. York*), Bruno Bézard (*LESIA*), Pascal Bordé (*IAS*), Linda R. Brown (*JPL*), Arnaud Cassan (*IAP*), Céline Cavarroc (*IAS*), Angela Ciaravella *INAF/OAPa*), Charles Cockell *OU*), Athéna Coustenis (*LESIA*), Camilla Danielski (*UCL*), Leen Decin (*IvS*), Remco De Kok (*SRON*), Olivier Demangeon (*IAS*), Pieter Deroo (*JPL*), Peter Doel (*UCL*), Pierre Drossart (*LESIA*), Leigh N. Fletcher (*Oxford*), Matteo Focardi (*Un. Firenze*), Francois Forget (*LMD*), Steve Fossey (*UCL*), Pascal Fouqué (*Obs-MIP*), james Frith (*UH*), Marina Galand (*Imperial College*), Patrick Gaulme (*IAS*), Jonay I. González Hernández (*IAC*), Davide Grassi (*INAF/IFSI Roma*), Matt J. Griffin (*Cardiff*), Ulrich Grözinger (*MPIA*), Manuel Guedel (*Un. Vienna*), Pactrick Guio (*UCL*), Olivier Hainaut (*ESO*), Robert Hargreaves (*Un. York*), Peter H. Hauschildt (*HS*), Kevin Heng (*ETH*), David Heyrovsky (*CU Prague*), Ricardo Hueso (*EHU Bilbao*), Pat Irwin (*Oxford*), Lisa Kaltenegger (*MPIA*), Patrick Kervella (*Paris Obs.*), David Kipping (*UCL*), Geza Kovacs (*Konkoly Obs.*), Antonino La Barbera (*INAF/IASF Palermo*), Helmut Lammer (*Un. Graz*), Emmanuel Lellouch (*LESIA*), Giuseppe Leto (*INAF/OACt*), Mercedes Lopez Morales (*IEEC*), Miguel A. Lopez Valverde (*IAA/CSIC*), Manuel Lopez-Puertas (*IAA-CSIC*), Christophe Lovis (*Obs. Geneve*) Antonio Maggio (*INAF/OAPa*), Jean-Pierre Maillard (*IAP*), Jesus Maldonado Prado (*IEEC*), Jean-Baptiste Marquette (*IAP*), Francisco J. Martin-Torres (*CAB*), Pierre Maxted (*Un. Keele*), Steve Miller (*UCL*), Sergio Molinari (*Un. Firenze*), David Montes (*UCM*), Amaya Moro-Martin (*CAB*), Olivier Mousis (*Obs. Besancon*), napoléon Nguyen Tuong (*LESIA*), Richard Nelson (*QMUL*), Glenn S. Orton (*JPL*), Eric Pantin (*CEA*), Enzo Pascale (*Cardiff*), Stefano Pezzuto (*Un. Firenze*), Ennio Poretti (*INAF/OAMi*), Raman Prinja (*UCL*), Loredana Prisinzano (*INAF/OAPa*), Jean-Michel Réess (*LESIA*), Ansgar Reiners (*IAG*), Benjamin Samuel (*IAS*), Jorge Sanz Forcada (*CAB*), Dimitar Sasselov (*CfA*), Giorgio Savini (*UCL*), Bruno Sicardy (*LESIA*), Alan Smith (*MSSL*), Lars Stixrude (*UCL*), Giovanni Strazzulla (*INAF/OACt*), Gautam Vasisht (*JPL*), Sandrine Vinatier (*LESIA*), Serena Viti (*UCL*), Ingo Waldmann (*UCL*), Glenn J. White (*OU*), Thomas Widemann (*LESIA*), Roger Yelle (*UoA*), Yuk Yung (*Caltech*) **and** Sergey Yurchenko (*UCL*)

[1]University College London, Gower street, London WC1E 6BT, UK
email: `g.tinetti@ucl.ac.uk`

Abstract. The science of extra-solar planets is one of the most rapidly changing areas of astrophysics and since 1995 the number of planets known has increased by almost two orders of magnitude. A combination of ground-based surveys and dedicated space missions has resulted in 560-plus planets being detected, and over 1200 that await confirmation. NASA's Kepler mission has opened up the possibility of discovering Earth-like planets in the habitable zone around some of the 100,000 stars it is surveying during its 3 to 4-year lifetime. The new ESA's Gaia mission is expected to discover thousands of new planets around stars within 200 parsecs of the

Sun. The key challenge now is moving on from discovery, important though that remains, to characterisation: what are these planets actually like, and why are they as they are?

In the past ten years, we have learned how to obtain the first spectra of exoplanets using transit transmission and emission spectroscopy. With the high stability of Spitzer, Hubble, and large ground-based telescopes the spectra of bright close-in massive planets can be obtained and species like water vapour, methane, carbon monoxide and dioxide have been detected. With transit science came the first tangible remote sensing of these planetary bodies and so one can start to extrapolate from what has been learnt from Solar System probes to what one might plan to learn about their faraway siblings. As we learn more about the atmospheres, surfaces and near-surfaces of these remote bodies, we will begin to build up a clearer picture of their construction, history and suitability for life.

The Exoplanet Characterisation Observatory, EChO, will be the first dedicated mission to investigate the physics and chemistry of Exoplanetary Atmospheres. By characterising spectroscopically more bodies in different environments we will take detailed planetology out of the Solar System and into the Galaxy as a whole.

EChO has now been selected by the European Space Agency to be assessed as one of four M3 mission candidates.

Keywords. planets and satellites: formation, planets and satellites: general, planetary systems, planetary systems: formation

1. EChO – overview

EChO will provide an unprecedented view of the atmospheres of planets around nearby stars. Those planets will span a range of masses (from gas giants to super-Earths), stellar companions (F, G, K, M) and temperatures (from hot to habitable). EChO will inherit the technology of CoRoT and Kepler to achieve photometric precision at the $10^{-4} - 10^{-5}$ level in the observation of the target star and extend this capability into the mid-infrared.

EChO will observe the atmospheres of planets already discovered by other surveys and facilities. If launched today, EChO would select $\sim$50 targets for atmospheric characterisation out of the 100+ confirmed transiting exoplanets. Most of these targets were discovered by dedicated ground-based transit/radial velocity search programmes (WASP, XO, HAT-P, HARPS, RoPACS etc.). A new generation of transit/radial velocity surveys (NG-WASP, MEarth, APACHE, HARPS-North, ESPRESSO etc.) will provide access to the population of Earth-mass planets orbiting bright late type-stars, e.g. GJ 1214b, 55 Cnc e. In the quest for habitable worlds outside our Solar System, EChO will be able to observe super-Earths in the temperate zone of M dwarfs - not the Earth's and Sun's twins, but rather cousins. Will they present equal opportunities for habitability?

The base-line design for the ESA proposal is a dispersive spectrograph covering continuously the 0.4-16μm spectral range. The spectral resolving power will be adapted to the target brightness, from several tens to several hundreds. The instrument will be mounted behind a 1.2-1.4m class telescope passively cooled. The stability and accuracy of the photometry is critical to the success of EChO and the design of the whole detection chain and satellite will be dedicated to achieving a high degree of photometric stability and repeatability. EChO will be placed in a grand halo orbit around L2. The thermal shield design will be optimised to provide a high degree of visibility of the sky over the year and an ability to repeatedly observe several tens of targets whatever the time of the year (Tinetti *et al.* 2011).

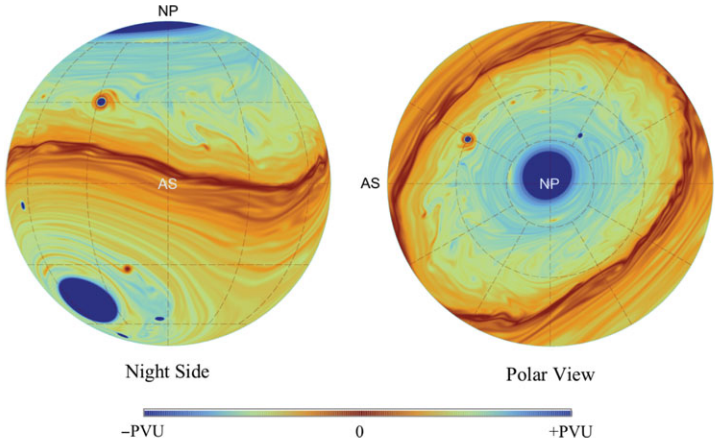

Figure 1. Maps of vorticity in the inertial reference frame and the rotating reference frame from 2-D and 3-D high-resolutions simulations of tidally locked hot Jupiters (Cho *et al.* 2003). We can appreciate the complexity of the flow with structures on an large range of scales.

2. Science return

2.1. *Atmospheric Dynamics of Hot-Jupiters and Hot-Neptunes*

EChO will provide much needed constraints on atmospheric dynamics and circulation models. This is done via careful, repeated observations. The following are the various types of observations that EChO can provide:

- Primary and secondary transits, leading to day and night side information
- Ingress and egress measurements, leading to horizontal/vertical structure information
- Non-transiting planet observations, providing information about the extra-tropics on the planet
- Host stars, providing information about the background and ionisation

Currently, what is lacking is good statistics and times series of observations to assess variability, which is expected to occur on a wide range of scales (Thrastarson & Cho 2010). An iterative approach will be used. First, using plausible vertical temperature profiles from full three-dimensional (3-D) general circulation models, spectra models can give information about the composition and its vertical distribution. The latter will then be inserted as input back into the 3-D models as either initial condition or self-consistently evolved distribution to obtain global temperature and flow distributions. When very high resolution calculations are needed to capture detailed physical or chemical effects, they can be carried out using vertically- or zonally-averaged two-dimensional (2-D) models, as appropriate.

At the cutting edge of the field is whether transient phenomena exist in the light curves and spectra obtained from hot Jupiters, as well as the implications of variability if it exists. Vortices and waves are long-lived, coherent features which should contribute heavily to variability on hot gaseous planets. The variability is expected to be slow and occurs on a large scale, as indicated by three-dimensional simulations. The resulting, computed power spectrum of the temperature field shows that the bulk of the energy is contained in the channel corresponding to a period of about 15 planetary days. The baroclinic instability may also contribute to variability; its basic mechanism is well understood, at least from a terrestrial standpoint. In the case of the hot Jupiter HD 209458b, the gravest (most unstable) mode has a wavenumber of between 2 and 3, while its growth period is about 10 planetary days. By comparison, the gravest mode in the terrestrial atmosphere has a wavenumber of 6 and a growth period of about 2 Earth days. The detection of variability in the atmospheres of hot Jupiters allows us to judge which are the dominant fluid instabilities at work and consequently determine their influence on the observed spectra. In general, general circulation simulations are dealing with a three-dimensional, non-linear problem involving multiple parameters. For example, the outcome of these simulations depend significantly on the initial conditions of the surface flow (Thrastarson & Cho 2010), which are presently unknown in the case of hot Jupiters. Furthermore, the predictions for the surface wind speeds carry an intrinsic range of uncertainty (Heng *et al.* 2011) which can only be calibrated out via direct measurements. The key point is that a pragmatic approach which couples transit observations with a hierarchy of theoretical models and simulations is the way forward towards increasing the predictive power of the general circulation simulations of hot Jupiter atmospheres.

2.2. *Upper Atmosphere*

Within our own solar system, the upper atmospheres of gas giants, both of which have been explored over recent decades both from Earth and from in-situ orbiting satellites, have been found to form regimes of complex interaction between the atmospheric gases, solar radiation, magnetospheres and their plasma population as well as the solar wind. These are regions of particular importance to investigate as they constrain the relative roles of external energy sources, including the magnetosphere/plasma environment, as well as constraining rates of atmospheric gas escape as well as other dynamical processes driven from the deeper atmosphere. In many cases upper atmospheres also feature auroral regions, where energetic particle precipitation deposit energy locally and generate optical emissions which can be observed from Earth, constraining atmospheric gases as well as the magnetic and plasma environments. EChO offers an unprecedented opportunity of expanding this exploration to solar systems outside of our own. We intend with EChO to explore the upper atmospheres of exoplanets, with the aim of addressing the following key science questions:

- What is the thermal structure and energy balance of exoplanet atmospheres? What are the characteristics of stellar forcing? What are the radiative time scales of atmosphere and how important are processes in Local Thermodynamic Equilibrium (LTE) versus those who are in non-LTE.
- What is the composition and vertical distribution of constituents, what chemical processes are active?
- What are the characteristics of the magnetic and plasma environments of exoplanets and how do these interact with the atmospheres?
- What are the rotation rates of exoplanet upper atmospheres?

Over recent years first direct spectroscopic observations have been made of atmospheres of extrasolar planets. Spectra observed during the transit have identified the NaI D lines, the H Ly line and ionised species (CII, SiI) in absorption (Charbonneau *et al.* 2000; Vidal-Madjar *et al.* 2004; Linsky *et al.* 2010). These observations placed first constraints on the structure of extrasolar planet upper-atmosphere. Simulations by Yelle (2004) have shown these observations to be consistent with thermospheric temperatures near 10,000 K, which in turn drive hydrodynamic escape and cooling of the thermosphere by adiabatic expansion. While allowing for detection of unexpected spectral signatures, we intend to specifically investigate amongst other the following lines:

- <u>H_3^+ emission (3.5-4.1 μm).</u> Of particular interest in the study of Gas Giants within our own solar system are emissions of H_3^+ which dominate Gas Giant emissions between 3 and 4 μm. As shown by Miller *et al.* (2006), H_3^+ is a powerful indicator of energy

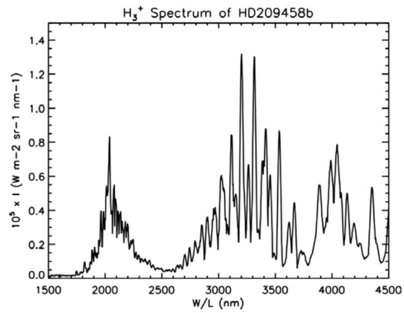

Figure 2. H_3^+ simulated spectrum for hot-Jupiter HD209458b (Koskinen *et al.* 2010). A model of the planet's upper atmosphere (Koskinen & Harris, private communication) was used to calculate the substellar column density of H_3^+ . This model is based on solving the one-dimensional equations of motion for dynamic expansion together with realistic heating rates and photochemistry for an atmosphere composed of hydrogen and helium. The results agree roughly with those of Yelle (2004) and García Muñoz (2007) for the same planet.

inputs into the upper atmosphere of Jupiter, suggesting a possible significance in exoplanet atmospheres as well. Simulations by Yelle (2004) and Koskinen *et al.* (2007) have among other investigated the possible importance of H_3^+ as a constituent and infrared emitter in exoplanet atmospheres. One particular finding of these calculations and those of Yelle (2004) is the fact that close-orbiting extrasolar planets ($R \leqslant 0.2$ AU) may host relatively small abundances only of H_3^+ due to the efficient dissociation of H_2, a parent molecule in the creation path of H_3^+. As a result, the detectability of H_3^+ may depend on the distance of the planet from the star. Fig. 2 shows an example of a simulated emission spectrum of H_3^+ for HD209458b at resolution of R=300, which matches the anticipated EChO resolution in this spectral range.

• CH_4 emission Observations of the auroral regions of Jupiter have given positive detections of CH_4 in emission, which are thought to be generated by energetic particle precipitation which penetrates below the homopause level, reaching stratospheric methane. Therefore, CH_4 can be regarded as a powerful constraint for processes of magnetosphere-atmosphere coupling. Swain *et al.* (2009) identified an unexpected spectral feature near $3.25\,\mu$m in the atmosphere of the hot-Jupiter HD 189733 b which was found to be inconsistent with LTE conditions holding at pressures typically sampled by infrared measurements. They proposed this feature to result from non-LTE emissions by CH_4, indicating that non-LTE effects may need to be considered, as is also the case in our solar system for planets Jupiter and Saturn as well as Titan. We intend to specifically address this question with EChO, making use of the improved observing conditions from orbit.

2.3. *The chemistry of Jupiters and Neptunes*

Although it is likely that thermochemical equilibrium prevails in the deeper, hotter regions of the atmospheres of extrasolar giant planets, two main processes can drive the atmosphere out of equilibrium: 1) *transport-induced quenching* and 2) *photochemistry.*

(*a*) In the first process, temperatures in the radiative portion of the exoplanet atmosphere may be cool enough that energy barriers to kinetic reactions are difficult to overcome, so that chemical kinetic time scales can become large. If the vertical transport time scales drop below the chemical kinetic time scales, the mole fractions of some spectroscopically important species may be "quenched" or frozen in at abundances representative of deeper pressure levels (Prinn & Barshay 1977), leading to disequilibrium compositions in the observable regions of the exoplanet atmosphere.

(*b*) In the second process, the energy delivered from the absorption of stellar ultraviolet radiation can excite atmospheric molecules or break chemical bonds, setting off a series of chemical reactions that lead to the production of disequilibrium constituents (Yung & Demore 1999). For giant planets close to their host stars, this disequilibrium photochemical mechanism is a particularly effective process (Liang *et al.* 2003, 2004; Zahnle *et al.* 2009a,b; Line *et al.* 2010), as long as atmospheric temperatures are not so high as to drive the composition back to equilibrium.

The relative importance of thermochemical equilibrium, photochemistry, and transport-induced quenching in controlling the observed composition largely depends on the planet's thermal structure, which in turn depends on the planet's orbital distance and metallicity and the host star's luminosity and stellar type. The host star's chromospheric activity level and the overall UV flux incident on the planet can also affect the photochemistry, but properties like planetary mass or radius play less of a role.

The importance of the thermal structure in controlling chemistry is known. The thermal structures of different Jupiter- or Neptune-mass planets can lie within very different thermochemical equilibrium regimes, affecting not only the equilibrium composition but the effectiveness of disequilibrium processes like photochemistry. A planet like HD 209458b that orbits very close to a bright G0V star is expected to get very hot by planetary standards, which makes it more likely that gas-phase species like TiO, metal sulfides, or Na manage to remain in the gas phase rather than being tied up in condensates (e.g., Hubeny *et al.* 2003; Visscher *et al.* 2006). Silicate cloud formation likely occurs at lower pressures (higher altitudes) on hotter planets, with an increased chance of the stellar radiation interacting with these cloud layers. The thermal profile for HD 209733b lies solidly within the N_2 and CO stability fields (e.g., Lodders & Fegley 2002), making these more photochemically stable molecules the dominant carriers of nitrogen and carbon, thereby reducing the effectiveness of photochemical processes. Moreover, the possible presence of a thermal inversion on the dayside would help drive the chemistry back to equilibrium despite the strong UV flux incident on the planet (Moses *et al.* 2011). Disequilibrium processes on cooler planets like HD 189733b that orbit a fainter K2V star are expected to be more important (Line *et al.* 2010; Moses *et al.* 2011), due to the more sluggish rates of the chemical processes driving the composition back toward equilibrium. Some key molecules like CO, H_2O, and CO_2 may have vertical profiles that remain close to equilibrium predictions on on these cooler "hot Jupiters" like HD 189733b, but transport-induced quenching may allow CH_4 and NH_3 to be much more abundant in the few bar to few mbar region than is expected based on equilibrium, and photochemistry might lead to the production of nitriles like HCN and unsaturated hydrocarbons like C_2H_2 that can affect spectral behavior at visible and infrared wavelengths (Moses *et al.* 2011).

In general, the cooler the exoplanet, the more important that disequilibrium processes are likely to be. This trend is especially true for planets like GJ 436b that orbit close to weaker M stars such that the temperature structure lies within the CH_4 stability field rather than the CO stability field. The carbon-hydrogen bond in CH_4 is much weaker than the carbon-oxygen bond in CO, helping to free up carbon for disequilibrium processes. Complex hydrocarbons and nitriles may be produced on such planets (Zahnle *et al.* 2009b; Moses *et al.* 2011).

2.4. *Super-Earths around M-dwarfs: what should we expect?*

EChO will have the capability to perform transit spectroscopy of Super-Earths near or in the habitable zones of M-dwarf stars. These planets will be of immense scientific interest, as their climates may be comparable to those of the terrestrial planets in our own

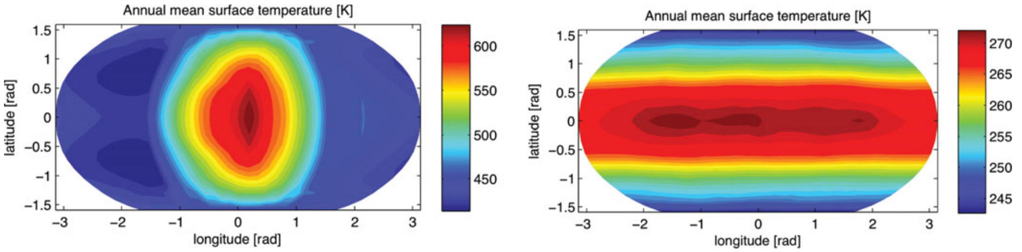

Figure 3. Simulations of the climate of a $R = 1.8R_E$ rocky planet with CO_2-dominated atmosphere around an M-class star of luminosity 0.013 L_s (Wordsworth et al.,). Two cases: hot (orbit 0.05 AU, $T_p \sim 400$ to 650 K) resonance 1:1, cold (orbit 0.22 AU, $T_p \sim 230$ to 280 K) resonance 1:10.

system. In particular, if they are rich in H_2O and have surface temperatures and pressures compatible with liquid water, they may potentially support Earth-like life. In general, the atmospheres of terrestrial exoplanets are expected to depend strongly on details of their formation and subsequent evolution, which means they are more difficult to predict theoretically than gas giants. However, M- dwarfs have some unique features that have already been predicted to make the climates of planets in their habitable zones very different from those in our own Solar System. First, they are relatively faint, so planets must be close in to receive Earth-like amounts of insolation from them. This means that terrestrial exoplanets in M-dwarf habitable zones might be in tidally resonant or locked orbits (see Fig. 3). As in the hot Jupiter case (§6.2), tidal locking can cause super-rotation in the planet's upper atmosphere, with potentially observable consequences. Tidal locking may also have serious consequences for habitability, as volatiles such as H_2O will tend to evaporate on the light side and freeze on the dark side of the planet. In the most extreme cases, the entire atmosphere can even condense out on the dark side. However, modelling has indicated that there are also many scenarios in which locked planets can sustain atmospheres and water cycles. For example, a Super-Earth with a dense atmosphere and a global ocean could efficiently transport heat across its surface and hence maintain a stable climate. One alternative to the scenario of tidal locking is spin-orbit alignment. A planet in a relatively eccentric orbit may escape synchronisation and establish a rotational spin that is some multiple of its orbital period, as happened to the planet Mercury (Correia & Laskar 2004). The climates of terrestrial planets around M-stars will also be altered due to the red-shifted stellar spectra. Red-shifting of the spectrum decreases Rayleigh scattering, so the bond albedos of M-class terrestrial exoplanets should generically be lower than those of planets in the Solar System. This theoretical prediction will be directly testable by EChO through secondary transit measurements in the optical. One side effect of this difference is that greenhouse warming by dense atmospheres becomes more effective than on Earth (Wordsworth *et al.* 2010), which alters the range of orbits for which habitable conditions are possible. Another unusual feature of M-class stars is their increased magnetic activity, which leads to a stronger stellar wind and more stellar flares (Segura *et al.* 2010). Increased stellar wind means increased atmospheric erosion, the consequences of which are still poorly understood for terrestrial exoplanets. The problem of H_2/He escape is a particularly critical one for planets intermediate in mass between the Earth and Neptune, as it ultimately determines the boundary between rocky and ice/gas giants. By studying the atmospheric composition (secondary transit) and probing the scale height through primary transit measurements (the scale height would be noticeably larger for a hydrogen-rich type of atmosphere), EChO will be able to investigate this vital scientific question directly.

In addition to the basic parameters described above, a planet which harbours life may also exhibit astronomical biosignatures The Earth's atmosphere contains an imprint of life from so-called biomarker molecules such as molecular oxygen (O_2), ozone (O_3) and nitrous oxide (N_2O). Theoretical studies (Grenfell *et al.* 2010; Segura *et al.* 2005) have begun to explore the extensive parameter range of potential biomarker spectral signals, assuming a similar development as the Earth and varying e.g. planetary and atmospheric mass, star class, position in the HZ, biosphere etc. Results suggest a strong dependency of the biomarker responses depending upon the class of the central M-star. Care is needed to distinguish true biomarker signals from so-called "false- positives" i.e. cases where planetary atmospheres "mimic" life (Selsis *et al.* 2002) due to inorganic chemical processes producing biomarkers – for example, strong CO_2 photolysis eventually leading to molecular oxygen production. Ozone features a strong infra-red absorption band at 9.6 μ m, easily measurable by EChO, and it may be present in large amounts over a wide range of oxygen concentrations (Segura *et al.* 2003). In this sense, ozone is a good biomarker. However, its photochemistry is complex (WMO, 1998) and is influenced by trace amounts of nitrogen-, chlorine-, and hydrogen-oxides whose abundances are difficult to constrain. Sources of nitrous oxide (N_2O) into Earth's atmosphere (IPCC TAR) are almost exclusively associated with microbial activity. It absorbs mostly in the troposphere with bands at e.g. at 7.8 and 3.9 μm. It is an excellent biomarker from the point of view that inorganic (non-life) production identified so far on the Earth is negligible, implying that false-positives are unlikely. However, its absorption features are weak for typical modern Earth abundances and measurements are extremely challenging. Atmospheres with weak UV-B could favour the build-up of large atmospheric N_2O abundances because its photolytic sink is weak in such cases.

Planets with no atmosphere

We expect that Super-Earths with no or negligible atmosphere would show large variations in intensity as a function of planetary phase. The MIR variability is driven by the difference in day-night surface temperatures. This variability in surface temperature should be relatively high, as a thin atmosphere has a very limited heat capacity to buffer its climate and even out day/night variations.

2.5. *Linking atmospheres and interiors*

The ability of EChO to fully characterise an exoplanetary atmosphere in its composition and thermal structure will provide major improvements for interior models as well. Except for the Earth and the Moon, there is no direct measurements of the deep structure of the planets, as this investigation requires a network of seismometers for terrestrial planets, or techniques similar to the asterosismology for gaseous giants. Nonetheless, the internal structure of planetary bodies in the solar system is, even if not precisely, relatively well understood. Planetary bodies can be split into three main families (Fig. 4) which are: i) the terrestrial planets (or solid planets), ii) the giant planets (or gaseous), and iii) the intermediate planets which are in between the two extreme cases.

The giant planet family

Giant planets are mostly made of hydrogen and helium and are expected to always be in gaseous form (Guillot 2005). Because they play a tremendous role in shaping planetary systems (Tsiganis *et al.* 2005) determining precisely their internal structure and composition is essential to understand how planets form. Contrary to solid planets, they are relatively compressible and the progressive loss of heat acquired during their formation is accompanied with a global contraction. Inferring their internal composition

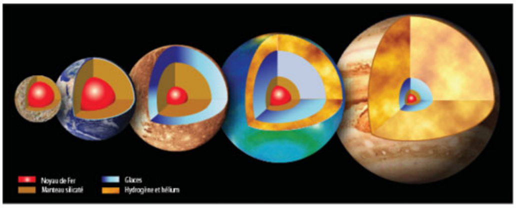

Figure 4. Internal structures of planets (not at scale). The three sub-families on the left are part of the terrestrial family (see text for detail). Giant planets (Jupiter-like) are on the right. Neptune – like planets, are on the fourth position from the left.

thus amounts to understanding how they cool. Fortunately, the dominance of hydrogen and helium implies that the degeneracy in composition (i.e. uncertainty on the mixture of ices/rocks/iron) is much less pronounced than for solid planets, so that the relevant question concerns the amounts and all elements other than hydrogen and helium, i.e. heavy elements, that are present.

The determination of sizes from primary transit measurements and masses from radial measurements have yielded in some cases a constraint on the mass of heavy elements present in the interior that is relatively independent of model hypotheses (Sato *et al.* 2005; Ikoma *et al.* 2006) and otherwise global tendencies showing that this mass is correlated with the metallicity of the parent star (Guillot *et al.* 2006; Burrows *et al.* 2007; Guillot 2008). However, several problems arise. First a large fraction of the known transiting planets are larger than expected, even when considering that they could be coreless hydrogen-helium planets (Bodenheimer *et al.* 2001; Guillot & Showman 2002; Baraffe *et al.* 2003; Guillot *et al.* 2006; Burrows *et al.* 2007; Guillot 2008). There is thus missing physics that is to be identified. Second, we do not know whether these heavy elements are kept inside a central core or distributed inside the planet. This influences how they cool (Guillot 2005; Baraffe *et al.* 2008) and is crucial in the context of formation scenarios (Lissauer & Stevenson 2007). Third, the complex dynamics of the atmosphere of heavily irradiated planets that constitutes the outer boundary condition of evolution models is poorly understood. This has direct consequences for our ability to accurately predict the evolution of these planets (Guillot & Showman 2002; Guillot 2010).

The terrestrial family

Three different sub-families of planets can be considered from left to right in Fig. 4: Mercury-like planets mostly composed of an iron core and a thin layer of silicates, Super-Earth made of an iron core and a thick silicate mantle (such as Venus, Mars and the Earth) and Ocean-planets made of iron, silicates, and water (similar to icy moons of Jupiter and Saturn). Super-Earths are composed of an internal iron-rich core and a thick silicate mantle (lower mantle) covered by a thin layer of low-pressure silicates similar to the upper mantle on Earth, and a very thin liquid layer (like Earth-oceans). Ocean-planets are composed of an iron core, a silicate mantle, and a thick icy layer surrounded by a thin ocean or icy crust at the surface.

For a given mass, one would expect Ocean-like planets have a smaller metallic core and silicate mantles, but also a larger radius than for Earth-like planets because icy materials are lighter than silicates. On the contrary, the radius of a much denser Mercury-like planets is about 80% that of an Earth-like planets (Valencia *et al.* 2007; Grasset *et al.* 2009). Mass - Radius measurements, though, do not give unique solutions. For example, a silicate-rich planet surrounded by a very thick atmosphere could provide the same mass and radius of an ice-rich planet with no atmosphere! (Adams *et al.* 2008). EChO will unravel the ambiguity through primary transit spectroscopic observations in the optical and IR, providing the bulk composition of the atmospheres when they are present. If EChO detects an atmosphere which is not primarily made of helium and hydrogen, thus the planet is most certainly from the terrestrial family, which means that the thickness of the atmosphere is expected to be negligible with respect to the planetary radius. If this is the case, an extensive literature (Léger *et al.* 2004; Valencia *et al.* 2006, 2007; Sotin *et al.* 2007; Seager *et al.* 2007; Adams *et al.* 2008; Grasset *et al.* 2009) can be fully exploited to characterise the inner structure of the new planet.

The intermediate family

Planets in between the gas giants and the small solid terrestrial planets are key to understand the formation of planetary systems. The existence of these intermediate planets close to their star, as found by radial velocity surveys, is already crucial to highlight the shortcomings of theoretical models (Mordasini *et al.* 2009). (i) Standard planet formation scenarios predict that embryos of sufficient mass (typically above 5 Earth masses) should retain some of the primordial hydrogen and helium from the protoplanetary disc. With EChO measurements, we will probe which planets indeed possess a hydrogen helium atmosphere and directly test the conditions of planet formation. (ii) The two only intermediate planets that we can characterise, Uranus and Neptune, are significantly enriched in heavy elements, in the form of methane (Guillot 2005). The reason for this enrichment is unclear: is it due to upward mixing, early or late delivery of planetesimals? EChO will allow these measurements in many planets thereby providing observations that are crucial to constrain these models. (iii) We do not know where to put the limits between solid, liquid and fluid (gaseous) planets. While EChO will not directly measure the phase of a planet as a whole, the determination of its size and of the composition of its atmosphere will be key to determine whether its interior is solid, partially liquid or gaseous.

3. Other science with EChO

While the vast majority of the EChO mission will be dedicated to exoplanet spectroscopy and its design will be fine-tuned for that cause, the ability to do spectroscopy with broad simultaneous wavelength coverage and high sensitivity makes EChO a superb tool to address a host of science cases, in particular:

- Direct spectroscopic characterisation of free-floating (and perhaps in rare cases resolved companion) brown dwarfs and planetary mass objects, with particular focus on constraining surface gravity and composition to compare free-floating planets to models of planets formed through core accretion. In particular, spectroscopic follow-up of L, T, and particularly Y dwarfs from the WISE mission allows confronting models of these very cool objects with observations.
- An important scientific question, is to understand how the elemental abundances of planets follow from the composition and chemistry of the disks in which they formed. The ability to obtain simultaneous visible to mid-IR spectra for variable young stellar objects could make profound contributions to our understanding of how changes in disk accretion and dust attenuation affect disk structure and the evolution of gas and dust composition in planet-forming disks (Ábrahám *et al.* 2009; Banzatti *et al.* 2011).
- Search for extrasolar moons. Exomoons are likely to be rocky bodies and thus offer the same potential of Earths/Super-Earths as possible havens for life. Their discovery would also reap immense new understanding of planet/moon formation. For transiting

planet systems, exomoons can be detected through two principal methods i) transit timing effects ii) exomoon transits (Kipping 2009a,b).

• Rocky transiting planets found with Kepler are unlikely to induce detectable radial velocity signals and thus the only way to confirm their planetary nature is to rule out the probable sources of astrophysical false positives, most pertinently blends (e.g. background eclipsing binaries) that mimic an exoplanet signature in the Kepler bandpass. By measuring the transit depth at multiple wavelengths, such scenarios can be easily excluded.

References

Ábrahám, P., Juhász, A., Dullemond, C. P., Kóspál, Á., van Boekel, R., Bouwman, J., Henning, T., Moór, A., Mosoni, L., Sicilia-Aguilar, A., & Sipos, N. 2009, *Nature*, 459, 224

Adams, E. R., Seager, S., & Elkins-Tanton, L. 2008, *ApJ*, 673, 1160

Banzatti, A., Testi, L., Isella, A., Natta, A., Neri, R., & Wilner, D. J. 2011, *A&A*, 525, A12

Baraffe, I., Chabrier, G., & Barman, T. 2008, *A&A*, 482, 315

Baraffe, I., Chabrier, G., Barman, T. S., Allard, F., & Hauschildt, P. H. 2003, *A&A*, 402, 701

Bodenheimer, P., Lin, D. N. C., & Mardling, R. A. 2001, *ApJ*, 548, 466

Burrows, A., Budaj, J., & Hubeny, I. 2007, *ApJ*, 668, 671

Charbonneau, D., Brown, T., Latham, D., & Mayor, M. 2000, *ApJ*, 529, L45

Cho, J., Menou, K., Hansen, B. M. S., & Seager, S. 2003, *ApJL*, 587, L117

Correia, A. & Laskar, J. 2004, *Nature*, 429, 848

García Muñoz, A. 2007, *Plan. Space Sci.*, 55, 1426

Grasset, O., Schneider, J., & Sotin, C. 2009, *ApJ*, 693, 722

Grenfell, J. L., Rauer, H., Selsis, F., Kaltenegger, L., Beichman, C., Danchi, W., Eiroa, C., Fridlund, M., Henning, T., Herbst, T., Lammer, H., Léger, A., Liseau, R., Lunine, J., Paresce, F., Penny, A., Quirrenbach, A., Röttgering, H., Schneider, J., Stam, D., Tinetti, G., & White, G. J. 2010, *Astrobiology*, 10, 77

Guillot, T. 2005, *Annu. Rev. Earth Plan. Sci.*, 33, 493

—. 2008, *Physica Scripta*, T130, 014023

—. 2010, *A&A*, 520, A27+

Guillot, T., Santos, N. C., Pont, F., Iro, N., Melo, C., & Ribas, I. 2006, *A&A*, 453, L21

Guillot, T. & Showman, A. P. 2002, *A&A*, 385, 156

Heng, K, Menou, K, Phillipps, P. J. 2011, *MNRAS*, 413, 2380

Hubeny, I., Burrows, A., & Sudarsky, D. 2003, *ApJ*, 594, 1011

Ikoma, M., Guillot, T., Genda, H., Tanigawa, T., & Ida, S. 2006, *ApJ*, 650, 1150

Kipping, D. 2009a, *MNRAS*, 392, 181

—. 2009b, *MNRAS*, 396, 1797

Koskinen, T., Aylward, A., & Miller, S. 2007, *Nature*, 450, 845

Koskinen, T., Cho, J.-K., Achilleos, N., & Aylward, A. D. 2010, *ApJ*, 722, 178

Léger, A., Selsis, F., Sotin, C., Guillot, T., Despois, D., Mawet, D., Ollivier, M., Labèque, A., Valette, C., Brachet, F., Chazelas, B., & Lammer, H. 2004, *Icarus*, 169, 499

Liang, M.-C., Parkinson, C. D., Lee, A. Y. T., Yung, Y. L., & Seager, S. 2003, *ApJL*, 596, 247

Liang, M.-C., Seager, S., Parkinson, C. D., Lee, A. Y. T., & Yung, Y. L. 2004, *ApJL*, 605, 61

Line, M. R., Liang, M. C., & Yung, Y. L. 2010, *ApJ*, 717, 496

Linsky, J. L., Yang, H., France, K., Froning, C. S., Green, J. C., Stocke, J. T., & Osterman, S. N. 2010, *ApJ*, 717, 1291

Lissauer, J. J. & Stevenson, D. J. 2007, *Protostars and Planets V*, 591

Lodders, K. & Fegley, B. 2002, *Icarus*, 155, 393

Miller, S., Stallard, T., & Smith, C., *et al.* 2006, Royal Society of London Transactions Series A, 364, 3121

Mordasini, C., Alibert, Y., & Benz, W. 2009, *A&A*, 501, 1139

Moses, J. I., Visscher, C., Fortney, J. J., Lewis, N. K., Showman, A. P., Marley, M. S., Griffith, C. A., & Friedson, A. J. 2011, *ApJ*, 737, id.15

Prinn, R. & Barshay, S. 1977, *Science*, 198, 1031

Sato, B., Fischer, D. A., Henry, G. W., Laughlin, G., Butler, R. P., Marcy, G. W., Vogt, S. S., Bodenheimer, P., Ida, S., Toyota, E., Wolf, A., Valenti, J. A., Boyd, L. J., Johnson, J. A., Wright, J. T., Ammons, M., Robinson, S., Strader, J., McCarthy, C., Tah, K. L., & Minniti, D. 2005, *ApJ*, 633, 465

Seager, S., Kuchner, M., Hier-Majumder, C. A., & Militzer, B. 2007, *ApJ*, 669, 1279

Segura, A., Kasting, J. F., Meadows, V., Cohen, M., Scalo, J., Crisp, D., Butler, R. A. H., & Tinetti, G. 2005, *Astrobiology*, 5, 706

Segura, A., Krelove, K., Kasting, J. F., Sommerlatt, D., Meadows, V., Crisp, D., Cohen, M., & Mlawer, E. 2003, *Astrobiology*, 3, 689

Segura, A., Walkowicz, L. M., Meadows, V., Kasting, J., & Hawley, S. 2010, *Astrobiology*, 10, 751

Selsis, F., Despois, D., & Parisot, J. 2002, *A&A*, 388, 985

Sotin, C., Grasset, O., & Mocquet, A. 2007, *Icarus*, 191, 337

Swain, M. R., Vasisht, G., Tinetti, G., Bouwman, J., Chen, P., Yung, Y., Deming, D., & Deroo, P. 2009, *ApJ*, 690, L114

Thrastarson, H. T. & Cho, J. 2010, *ApJ*, 716, 144

Tinetti, G., *et al.* 2011, *Experimental Astronomy*, submitted

Tsiganis, K., Gomes, R., Morbidelli, A., & Levison, H. F. 2005, *Nature*, 435, 459

Valencia, D., O'Connell, R. J., & Sasselov, D. 2006, *Icarus*, 181, 545

Valencia, D., Sasselov, D. D., & O'Connell, R. J. 2007, *ApJ*, 665, 1413

Vidal-Madjar, A., Désert, J., Lecavelier des Etangs, A., Hébrard, G., Ballester, G. E., Ehrenreich, D., Ferlet, R., McConnell, J. C., Mayor, M., & Parkinson, C. D. 2004, *ApJL*, 604, L69

Visscher, C., Lodders, K., & Fegley, B. 2006, *ApJ*, 648, 1181

Wordsworth, R. D., Forget, F., Selsis, F., Madeleine, J.-B., Millour, E., & Eymet, V. 2010, *A&A*, 522, A22

Yelle, R. V. 2004, *Icarus*, 170, 167

Yung, Y. L. & Demore, W. B., eds. 1999, Photochemistry of planetary atmospheres

Zahnle, K., Marley, M., Freedman, R., Lodders, K., & Fortney, J. 2009a, *ApJ*, 701, L20

Zahnle, K., Marley, M. S., & Fortney, J. J. 2009b, *ApJ* submitted (arXiv:0911.0728)