Characterizing exoplanets

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However you date it, 2013 was the year that the science of extrasolar planets came of age. It was 21 years since Wolszczan & Frail’s [1] report of an unexpected planet-sized companion around the millisecond pulsar PSR 1257+12, and 18 years after Mayor & Queloz announced that they had found the first planet that looked like something recognizable from the Solar System perspective around the Sun-like star 51 Pegasi [2]. Since that time, there has been no holding the subject. At the time of writing, the internationally recognized Extrasolar Planets Encyclopaedia [3] is reporting over 1000 confirmed exoplanets, and NASA’s Kepler spacecraft has identified over 3500 candidate planets, as yet to be confirmed [4].

The Extrasolar Planets Encyclopaedia’s list covers over 780 planetary systems, of which just over a fifth are multiple planet systems [3]. Of these, 11 have more than five planets and two have as many as seven planets in their system—HD10180 and Kepler 90. The Kepler 11 system is remarkable for the range of masses detected—from 95% of the mass of Jupiter (M_J) down to just 2.3 Earth masses (M_E), giving the system quite a ‘familiar’ feel, at least as far as planetary masses are concerned. Kepler 11 itself is also quite Sun-like as a G6V star. (The planetary periods range from 10 to 118 days, much shorter than our Solar System, however.)

Planetary masses range from 0.001 M_J to 47 M_J, well beyond the limit at which deuterium burning might commence. Orbital eccentricities as high as $e = 0.97$ have been reported, and periods as short as 4 h 15 min and as long as 200 years have been deduced from the data. All in all, a picture is emerging of exoplanets occupying a very extended parameter space.
This issue of the Philosophical Transactions of the Royal Society A results from the Discussion Meeting ‘Characterizing exoplanets: detections, formation, interiors, atmospheres and habitability’ that took place at the Royal Society’s London premises on 11–12 March 2013, immediately followed by a further 2 day workshop at the Royal Society’s Kavli Centre. This meeting attracted considerable interest, with over 200 registered attendees, and 18 presentations, most of which are represented in this issue. The meeting organizers took the view that the time had come to move on from just the detection of exoplanets, important though that was and remains today, to their characterization—just what progress can be made in understanding these alien bodies in and of themselves, in much the same way that planetary scientists can characterize the planets of our own Solar System? So the meeting brought together those who had been in the forefront of exoplanet discovery with scientists who were beginning, through observations and modelling, to understand them as individual worlds. The meeting further brought together the communities working on this burgeoning subject, the astronomers, the planetologists, but also anyone interested in astrobiology and habitability aspects.

Hugh Jones et al. [5] focus on the detection and characterization of M dwarfs (cool, low-mass stars) which dominate the stellar population but are nevertheless the subject of a small number of radial velocity measurements. As a consequence, some of the inferences (such as the similarity with the semi-major axis distribution of more massive stars implying compatible formation and migration processes) could be biased. The authors point to the departure of the observed planet formation around low-mass stars, which drops off faster than expected in stellar mass theories. Jones et al. stress the importance of analysing the wavelength sensitivity of radial velocity signals and of combining observational datasets and different reduction methods from available archives in order to confirm planetary companion detections and compensate for the M dwarf detection issues.

Given the great diversity of exoplanetary systems that are showing up from detections and candidates that we now have, we are entitled to ask questions about just how such systems have come into being. Richard Nelson, Alessandro Morbidelli and Olivier Grasset give some of the answers to these questions. Nelson et al. [6] report on model results which demonstrate that while it is possible to explain low and medium mass planets that orbit in short periods, it is very difficult to explain the large, ‘hot Jupiters’ that observations have shown to be widespread. They propose that a self-consistent model for gas envelope accretion and more sophisticated disc models are required if models are to reproduce ‘hot Jupiter’ formation. Morbidelli [7] emphasizes the unusual nature of our Solar System, with the giant planets comfortably separated from their much smaller, inner neighbours. That said, cases like ours are still worth investigating more generally and placing into context with new discoveries in mind. Morbidelli concludes that, given the narrowness of our habitable region, finding a system that looks like ours is no guarantee of any of the rocky planets being habitable. Where large planets have migrated into the inner planetary system, smaller planets may be too close to their stars to be habitable or even scattered out of the system altogether, and the situation is even less promising for exo-Earths, should the giant planet have an eccentric orbit. One final scenario for habitability is that giant planet cores, but no giant planets, form and migrate inward. Morbidelli concludes that these may disrupt the formation of planets as small as the Earth, but may themselves become habitable. Just this type of planet may be the explanation for several of the Kepler candidates, according to Grasset and co-workers [8]. They consider planets in the 30–100 Earth-mass range, such as Kepler-52b, Kepler-52c and Kepler-57b. In their scenario, these may be gas giants that have somehow been stripped to their rocky cores, which are then very dense.

Key to characterizing exoplanets, in terms of their atmospheric composition, are reliable atomic and molecular data. This often means going beyond what has traditionally been available, particularly in terms of extending the temperature range for which the data are suitable. The identification of water in the ‘hot Jupiter’ HD 209458b by Tinetti et al. [9] was made possible by the inclusion of the most extensive and reliable BT2 line list, which contains some 500 million individual transitions [10]. This line list had been developed by first principles calculations, which had been validated and empirically refined using the best available experimental data due to
Peter Bernath and many others. So contributions such as Bernath’s [11] to this issue play a vital role in the task of unravelling the riddle of just what exoplanets are like. Here he highlights the importance of experimental measurements for molecules such as methane and ammonia, for which considerable effort is still needed to validate and adjust the new computed line lists [12] that are needed to constrain models of exoplanet atmospheric composition derived from spectroscopic observations.

Without waiting for bigger, better telescopes, however, there has been great progress over recent years in imaging exoplanets directly, even though they are faint objects compared with the stars they orbit. Anne-Marie Lagrange reports [13] that, using telescopes such as the 10 m Keck telescope and ESO’s 8 m VLT, it has been proved possible to detect planets in the 1–10 M J range at distances approximately greater than 5 AU, all the way out to 2000 AU and more. She concludes that even the relatively few planets known from direct imaging have provided a challenge to models of planetary system formation, contrasting the core-accretion versus gravitational-instability dichotomy. Lagrange looks forward to an era of space-based telescopes that will allow the direct imaging of planets smaller than Jupiter to be accomplished. Following this, Giovanna Tinetti looks at the range of options for such space missions [14]. She highlights the achievements of current techniques, and outlines a range of steps that need to be taken if the field of observational exoplanetology is to make progress in the coming decade or so.

Following on from Bernath’s review of the data available and being developed for exoplanet characterization, Thérèse Encrenaz [15] and Ignace Snellen [16] make important contributions in understanding what can be expected from the increasing use of infrared spectroscopy to study these bodies. There is already great anticipation of what may result from the James Webb Space Telescope, and projects such as the EChO proposal [17] to the European Space Agency hold out the prospect of Earth-orbiting infrared spectroscopic observatories, dedicated to exoplanet characterization, even if the Agency does not want to proceed with them at this point in time. But much can still be done from ground-based telescopes. So Encrenaz sets out a systematic approach to choose the best possible targets for spectroscopic studies when using our existing observatories, based on planetary mass, orbital distance and the type of host star. She then outlines ways of optimizing the spectral range to be studied. Snellen’s paper outlines the progress that has been made already in using high-resolution spectroscopy to study CO in hot Jupiters, and what we can learn from this for detecting potential biomarker gases in Earth-like planets. His conclusion is that, while the contrast required is probably only three times as great as his team are already achieving for their hot Jupiter work, much larger collecting areas are required, because suitable target stars are much fainter than those that host the hot Jupiters. He suggests, though, that the lower image quality required for spectroscopy means that ‘flux collectors’ rather than highly focused, diffraction-limited, telescopes will be sufficient.

Even when we have spectroscopic data, understanding just what they are telling us about the characteristics of an exoplanet’s atmosphere is far from simple. Caitlin Griffith’s paper [18] warns us that there are major obstacles to be overcome in disentangling several competing models: spectral studies typically probe several scale heights, which can involve looking at many layers with different temperatures and concentrations of the species being studied. A lack of detailed knowledge about the physical and chemical structures of a planet’s atmosphere can make it difficult to extract unique and meaningful information from the spectra. She suggests combining optical and infrared data, as well as information derived from primary and secondary transits as a way of tying down some of the many variable parameters than can go into atmospheric models.

Some of the chemical reasons behind the complexity of exoplanetary atmospheres are explored by Julianne Moses [19], who asks just why is getting a firm grip on their composition so difficult? On a positive note, she finds that ‘warmer’ hot Jupiters, dominated by H2O and CO, and ‘cooler’ hot Jupiters, where CH4 substitutes for CO, have fairly well characterizable spectra in the regions where H2O dominates. But they are likely to show up disequilibrium features resulting from the transport of products from CO–CH4 quenching and photochemistry in the spectral windows
where $\text{H}_2\text{O}$ is the most transparent—windows known as J, H, K, L, M and N in astronomical observations. Moses reviews a number of observations that indicate the presence of constituents resulting from disequilibrium chemistry occurring in exoplanet atmospheres in hot Jupiters and hot Neptunes.

Four of the papers in this issue deal with some of the expected physical properties of subsets of the 1000-plus confirmed planets available for study by (exo-)planetary scientists. Leigh Fletcher and Tommi Koskinen take on the Jupiter-class planets. Fletcher et al. [20] discuss a range of possible classification schemes and typologies for these bodies, based on chemistry and cloud cover, their metallicity, and whether or not atmospheric absorbers will produce temperature inversions. They also consider the effects of mixing on the vertical profiles of chemical species and how energy can be redistributed, particularly in the case of synchronously locked hot Jupiters. They conclude that the observed hot Jupiters form a broad continuum of planetary types, and that what we find out about these bodies will make us view our own cold Jupiter in a very different light from the way we understand it now. The rate at which hot Jupiters may be evaporating depends on a complex interplay between photochemistry and stellar-UV-driven radiative transfer, according to Koskinen and co-workers [21]. They find that there are two key regimes for thermal escape that are sharply divided, which they label as ‘stable’ and ‘unstable’. In the first, downward conduction and radiative cooling are able to balance stellar heating, and mass loss rates are well below those that the total energy coming into the planet could sustain. But in the unstable regime, the planetary atmosphere is expanded significantly as a result of stellar heating, and mass loss rates are much larger and close to the limit allowed by the available energy. The breakdown of $\text{H}_2$ molecules controls the boundary between the two regimes; once this starts, a positive feedback mechanism ensures that the boundary is relatively sharp.

At the other ‘end’ of the planetary scale, detections of (super-)Earth-sized planets are now making it imperative that modelling work is carried out on these bodies to assist in interpreting the data that are being collected. So Lars Stixrude [22] has carried out studies, based on scaling from known silicate and iron melting curves, combined with \textit{ab initio} calculations and experimental data, to determine the effects of accretion on these bodies in their early stages of evolution. This leads to the conclusion that super-Earths will be at least partially molten at the top and bottom of their mantles, and that dynamo actions are likely for all of these planets found so far. The resulting volcanism and the generation of magnetic fields will have important implications for the potential habitability of super-Earths. Going further, Francois Forget & Jeremy Leconte [23] suggest that the time is already ripe for modelling the kinds of climate conditions that may exist on terrestrial exoplanets. These models should be based on those already available for Venus, Earth and Mars, and consist of familiar components such as a dynamical core, radiative transfer solvers, methods to parametrize both turbulence and convection, and codes to take into account the phase changes due to volatiles. Based again on our experience of our own Solar System, however, Forget & Leconte warn that positive feedback effects, which may require only minor changes in conditions to be activated, can lead to climate instabilities such as runaway greenhouse global warming or snowball planet ice ages. This is a space well worth watching.

One of the strongest motivations for the exploration of our own Solar System is to look for possible habitats for life, where it might once have emerged or might still be clinging on, or could even appear in the future should the right conditions and the requirements as we understand them (liquid water, nutrients and energy sources in a stable environment) be present. Such possible habitable worlds include Mars and the sub-surface oceans of Jupiter’s moons Europa, Ganymede and Callisto and Saturn’s largest moon, Titan. Indeed much of the drive for exploring exoplanets—albeit at a distance—is that some of them may be in a ‘Goldilocks zone’ where conditions might be just right for them, to be habitable. If so, could Earth-bound astronomers detect life? Charles Cockell’s Popperian approach to the ‘habitable exoplanet’ issue is to start with the (rather sobering and conservative) negative hypothesis ‘Most habitable worlds in the cosmos will have no remotely detectable signs of life’ [24]. He then goes through the conditions for this hypothesis to be verified, before going on to see what would be needed for a majority of habitable
worlds to show signs of life that we could detect. The resulting paper here gives astronomers and planetary scientists a clear framework for future work, setting out what conditions have to be fulfilled if ours is not to remain the one biosphere of which we are certain.

These 16 papers represent an important contribution to the development of the rapidly expanding field of exoplanet science. They tackle key questions in the area. They show how much our knowledge has been developed in the past decade or so. But they also show how much there is still to be done, and how much the field needs its own dedicated instruments and space missions, if it is to live up to the promise of a prodigious enfant terrible and become a truly mature science. We have every confidence that the missions, the new ground-based observations and computer modelling will materialize. Our fellow citizens—scientists or otherwise—all want to know: ‘Are we alone in the Universe?’ Mature exoplanetology can help to provide the answer.

References