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Doppler spectroscopy as a path to the detection of Earth-like planets

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Doppler spectroscopy was the first technique used to reveal the existence of extrasolar planetary systems hosted by solar-type stars. Radial-velocity surveys led to the detection of a rich population of super-Earths and Neptune-type planets. The numerous detected systems revealed a remarkable diversity. Combining Doppler measurements with photometric observations of planets transiting their host stars further provides access to the planet bulk density, a first step towards comparative exoplanetology. The development of new high-precision spectrographs and space-based facilities will ultimately lead us to characterize rocky planets in the habitable zone of our close stellar neighbours.

During the past three decades, the development of astronomical instrumentation and the scientific development of new observational techniques made it possible to transform the old philosophical concept of 'plurality of worlds' in the Universe into an active field of modern astrophysics. Today, almost 2,000 planets orbiting other stars are known, and we are contemplating an even more exciting challenge: discovering Earth-like exoplanets with physical conditions suitable for the complex chemistry of life to develop.

Some of the most important discoveries in this field have been made using the technique of Doppler spectroscopy. These results are the focus of this Review. They illustrate the tremendous progress that has been made in our understanding of exoplanet populations in the Galaxy, and the role of the stellar environment in the formation of planetary systems.

The discovery of a whole new population of planets orbiting other stars has now moved the focus of exoplanet researchers to two main areas: the search for planets of lower and lower mass, and the precise characterization of the new-found planets. In the years to come, the rise of a new set of experiments, including ground-based giant telescopes and space-based missions dedicated to the detection and characterization of planets hosted by bright stars, will allow the next big steps in this research. These efforts will bring us closer to the goal of detecting and characterizing Earth-like exoplanets of rocky composition orbiting within the habitable zone of their host star.

Early history

How many planets are there in the Milky Way? How many planets are similar to Earth? It is interesting to look at the astronomical literature of the twentieth century for estimations of the number of planetary systems in the Galaxy. Before 1943, the values ranged from zero to, at most, a few systems. The formation of protoplanetary gaseous nebulae was thought to result from the tidal capture of a stellar envelope through a close encounter with another star[1]. The extremely low probability of such a small impact collision was at the origin of these quite pessimistic estimations of number of planetary systems. In the early 1940s, claims of the discovery of several systems[2,3], later found to be false, induced, in a couple of years, a complete paradigm shift[4]. Those estimates jumped to billions if not hundreds of billions. It is interesting that such a drastic change of thought was the result of spurious detections of planetary systems.

The use of variation of stellar radial velocity due to gravitational interaction with a massive planet was suggested as a detection method long before spectrographs achieved the high precision needed for such detections[5,6]. The radial-velocity technique, based on the variable Doppler shift of stellar absorption lines, is able to measure planetary orbital period, orbital eccentricity and minimum mass ($M\sin i$). The amplitude of radial-velocity variations depends on the planet mass and orbital distance. In the Solar System, Jupiter induces a $12\ \mathrm{m\ s^{-1}}$ radial-velocity signal on the Sun with a periodicity of 12 years, whereas Earth imprints a tiny $0.1\ \mathrm{m\ s^{-1}}$ signal at a 1-year period. The corresponding Doppler shifts on the stellar spectrum are, however, extremely challenging to measure ($\sim 10^{-8}$–10^{-10} of the wavelength), which hampered progress in this field for decades.

It was only during the 1980s that several ideas and technological solutions were proposed for new spectrographs, allowing radial-velocity precision of a couple of dozen metres per second[7]. Among the pioneers, credit has to be given to Campbell and Walker[7] for their survey of around 20 stars. With a hydrogen–fluoride absorption cell in front of their spectrograph, they demonstrated a radial-velocity precision of the order $15\ \mathrm{m\ s^{-1}}$. However, at the end of many years of monitoring, their efforts obtained a negative result: no detection of Jupiter analogues orbiting their small stellar sample of solar-type stars[8]. Another survey was initiated by Marcy and Butler[9] in 1988 at the Lick Observatory. Their iodine absorption cell gave, at that time, a similar precision of about $15\ \mathrm{m\ s^{-1}}$. The result, in 1994, of that survey was similar to the earlier one: no Jupiter analogues were found around 25 solar-type stars[9].

At the same time as these surveys of limited size, a few teams were operating efficient spectrographs of moderate precision (250–$500\ \mathrm{m\ s^{-1}}$) but on large stellar samples. Among the many thousands of stars surveyed (mostly the main sequence stars F, G, K and M), a few stars were used as standard by the different teams and provided dozens to hundreds of radial-velocity measurements. When analysing the velocities of one of these objects, HD 114762, Latham *et al.*[10] found a periodic variation of 84 days and an amplitude corresponding to a possible companion of 11 times the mass of Jupiter (M_J), on an eccentric orbit. Combining their data with complementary measurements acquired at Haute-Provence Observatory allowed the publication of a very precise orbit[10].

Was this companion a planet or low-mass brown dwarf? At that epoch, the community was inclined towards the second option — a result of its short period, rather large values for the orbital eccentricity and mass, all characteristics not expected for a gaseous giant planet similar to the ones of our Solar System. Based on the present observed diversity of detected exoplanets, this consensus is certainly

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not a definitive conclusion. However, one characteristic should be mentioned: HD 114762 is a metal-deficient star (for which metallicity $[\mathrm{Fe/H}] = -0.7$, where $[\mathrm{Fe/H}] = \log[A_{\mathrm{Fe}}/A_{\mathrm{H}}]$ star $- \log(A_{\mathrm{Fe}}/A_{\mathrm{H}})$ Sun and A is the abundance of a given chemical element). According to present-day observations and to state-of-the-art models of planetary formation, it seems difficult to form a massive planet in such a metal-poor environment[11] (see 'Chemical clues for stars with planets'). For instance, a recent high-precision 10-year-survey of more than 100 solar-type stars has not revealed one single gas-giant planet with metallicity significantly lower than −0.5 (ref. 12). In contrast with planet formation, the formation of low-mass stars is not strongly constrained by the metallicity of the star-formation environment. These facts suggest that HD 114762b is most likely to be a low-mass stellar companion. We should note, however, that a few low-mass companions with metallicity close to that of HD 114762 have been detected[11,13]. HD 114762 is the most massive of these outliers.

The discovery of 51 Pegasi b and its strange properties

At the beginning of the 1990s, two different approaches were used to determine precise stellar radial velocities. On the one hand, spectrographs with absorption cells in the beam of the spectrograph (hydrogen-fluoride cell or iodine cell)[14,15], and on the other hand, fibre-fed spectrographs with simultaneous calibration provided by a thorium lamp in a parallel fibre[16]. Both methods were aimed at providing a precise calibration in wavelength. In 1995, a comparable precision ($15\ \mathrm{m\ s^{-1}}$) was achieved by both techniques. However, one positive characteristic of the double-fibre spectrograph was its ability to obtain the final radial-velocity value a few seconds after the end of the observation sequence (an achievement not possible at the time for spectrographs using the absorption-cell technique). Furthermore, the double-fibre technique is more efficient in terms of photon noise, a crucial point to allow radial-velocity monitoring of a large sample of stars with moderate-sized telescopes.

In April 1994, with the new ELODIE spectrograph at Haute-Provence Observatory[16] (using the simultaneous calibration technique), Mayor and Queloz[17] initiated a systematic survey of 142 solar-type stars to search for brown dwarfs or giant planets. Included in that sample was 51 Pegasi, a metal-rich G2V type star, which was found to exhibit a periodic variation of its velocity with a period as short as 4.2 days. If resulting from the influence of a companion, the observed amplitude would indicate a minimum mass of a little less than half the mass of Jupiter[17]. This discovery revealed the first exoplanet hosted by a solar-type star and a first example of the family of so-called hot Jupiters.

Interestingly, such a short period was quite unexpected. The formation of gas-giant planets by agglomeration of ice particles was not supposed to be possible inside the 'ice-line'[18]. However, soon after this first detection, Lin *et al.*[19] showed that short-period gas-giant planets could result from the orbital migration of the young planet embedded in the accretion disk. This physical process was already described in the literature[20,21], but never incorporated in scenarios of planetary system formation.

Soon after the discovery of 51 Peg b, the detection of several short period planets was announced by Butler *et al*[22]. Clearly, 51 Peg b was not a unique object with exceptional characteristics.

Despite the run of detections, not all the community was convinced that these unexpected objects with short periods were indeed planets. However, a few crucial observations played a significant part in confirming their planetary nature. The detection of multi-planetary systems was strong evidence supporting the planetary explanation, but the most important observation was the first detection of a planetary transit.

HD 209458b is a hot Jupiter-like planet with an orbital period close to 3.5 days. During the night of the 9 September 1999, at the precise time derived from the radial-velocity ephemerides, the first transit of the planet was detected, this was followed by a second detection 7 days later[23]. The same host star was also scrutinized by another team and the transit detected[24]. The data also allowed researchers to derive the mean density of that gas giant, showing that it was as low as $0.3\ \mathrm{g\ cm^{-3}}$, less than half the mean density of Saturn. Observation of the transit was repeated with the Hubble Space Telescope the following year[25]. The amazing precision of that transit is a milestone of exoplanet research. Hot Jupiters are indeed real gas-giant planets. Not only did the transit curve put an end to alternative interpretations for the existence of hot Jupiters, but that observation, with its remarkable precision, also opened the door to space experiments dedicated to exoplanetary transits such as the Convection, Rotation and Planetary Transits (CoRoT) and Kepler missions, and future missions such as Transiting Exoplanet Survey Satellite (TESS), Characterising Exoplanet Satellite (CHEOPS) and Planetary Transits and Oscillations of Stars (PLATO).

A recent result refined our knowledge of 51 Peg b. Observing high-resolution spectra of stars hosting planets, it is possible to detect spectral fingerprints of a planet's atmosphere. Using this technique, significant absorption from carbon monoxide and water vapour were observed in the dayside atmosphere of 51 Peg b[26]. In this way, the radial velocity of the planet could be measured directly, allowing the determination of the planet/star mass ratio and orbital inclination. This gave a direct estimate of the mass of 51 Peg b of $0.46\ M_{\mathrm{J}}$.

An explosion of discoveries

In 1995, the radial-velocity precision achieved by the best instruments was about $15\ \mathrm{m\ s^{-1}}$. By 1996, improvements in the data-reduction software allowed the precision of the iodine-cell technique to be improved down to $3\ \mathrm{m\ s^{-1}}$ using the Hamilton Echelle Spectrometer at the Lick Observatory and Keck High Resolution Echelle Spectrometer (HIRES)[27]. The need to increase the precision of Doppler measurements is obvious because the amplitude of the radial-velocity wobble is directly proportional to the planetary mass.

Soon after the discovery of 51 Peg b[17], existing radial-velocity surveys of nearby solar-type stars were significantly expanded, and new ones started, with precision of $3\text{–}10\ \mathrm{m\ s^{-1}}$ (refs 16, 27–31). Additional hot-Jupiter discoveries quickly followed, aided by the relative ease of detection of their radial-velocity signals[22]. Over the next two decades, several hundred giant exoplanets were found, spanning a wide range of mass and orbital distance.

In 2003, a new gain in precision was achieved with the construction

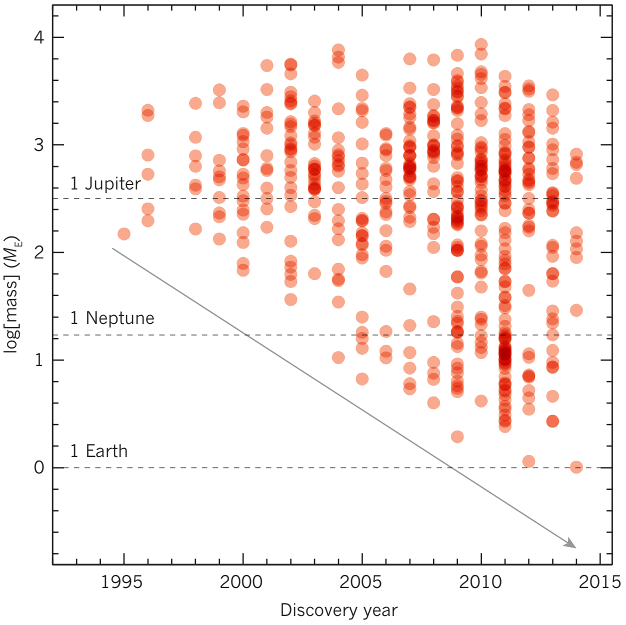

Figure 1 | Exoplanet discoveries as a function of time. The plot shows the minimum mass of the planets discovered by radial-velocity surveys as a function of discovery epoch. The horizontal lines denote the position of Earth, Neptune and Jupiter in this plot. The lower envelope of the points is illustrated by the solid line. This plot shows the incredible decrease in mass of the discovered planets, reflecting the increasing precision of radial-velocity surveys. Earth-mass planets are presently within reach and have been detected.

Table 1 | Some remarkable planetary systems discovered or characterized with Doppler spectroscopy

System name	Description	Comments
51 Pegasi[17]	1 hot Jupiter	First exoplanet found around a solar-type star
υ Andromedae[101]	3 gas giants within 2.5 AU	First multi-planet system identified
HD 209458 (refs 23, 24, 102)	1 transiting hot Jupiter	First transiting exoplanet found and well suited to atmospheric characterization owing to host-star brightness
HD 80606 (refs 103, 104)	1 transiting hot Jupiter	Highest known orbital eccentricity ($e = 0.93$) and misaligned orbit
GJ 436 (refs 57, 73)	1 transiting Neptune	First transiting Neptune, close-in but eccentric orbit and orbiting a nearby M dwarf
μ Arae (refs 56, 105)	1 close-in Neptune, 3 gas giants within 5 AU	Dynamically packed system of giant planets with inner low-mass object
55 Cnc[58,106]	1 transiting super-Earth, 4 gas giants within 6 AU	Dynamically packed system of giant planets with inner low-mass and intermediate-density object
HD 189733 (ref. 107)	1 transiting hot Jupiter	Well suited to atmospheric characterization owing to host-star brightness
HD 149026 (ref. 108)	1 transiting hot Saturn	Dense giant planet with large heavy element core
HD 69830 (ref. 59)	3 Neptunes within 0.6 AU	First system of close-in, low-mass planets
GJ 581 (refs 109, 110)	At least 2 super-Earths and 1 Neptune	First compact, low-mass system around an M dwarf
XO-3 (ref. 111)	1 transiting super-Jupiter	First planet showing a spin-orbit misalignment
HD 45364 (ref. 39)	2 gas giants within 0.9 AU	System in 3:2 mean motion resonance
HD 40307 (refs 79, 112)	4 super-Earths within 0.6 AU	Compact low-mass system with a potentially habitable planet
GJ 1214 (ref. 71)	1 transiting mini-Neptune	Low-mass, low-density object orbiting a nearby late M star
GJ 876 (ref. 113)	1 close-in super-Earth, 2 gas giants and 1 Neptune within 0.33 AU	Three outer planets locked in a 4:2:1 Laplace resonance similar to the Galilean moons of Jupiter
WASP-8 (ref. 114)	1 transiting hot Jupiter	Retrograde and misaligned orbit
HD 10180 (ref. 115)	Up to 7 planets within 3.5 AU, mostly Neptunes	Most populated exoplanet system known so far
HD 85512 (ref. 76)	1 super-Earth at 0.26 AU	Potentially habitable planet with a radial-velocity amplitude of 0.7 m s^{-1}
HD 97658 (ref. 69)	1 transiting super-Earth	Intermediate-density object orbiting a bright K dwarf
GJ 3470 (ref. 72)	1 transiting Neptune	Nearby M-dwarf host
α Centauri B[33]	1 short-period Earth-mass planet	Closest planetary system to the Sun
GJ 667C[78]	2 super-Earths	Potentially habitable planet

of the High Accuracy Radial Velocity Planet Searcher (HARPS) spectrograph at La Silla Observatory in Chile[32]. This fibre-fed vacuum spectrograph allows routine precision better than 1 m s^{-1}. This is still the most precise instrument for exoplanet detection. Following this and other developments, a large number of systems with planets smaller than Neptune could be detected (Fig. 1). Especially striking is the continuous decrease in the mass of detected exoplanets — an amazing improvement from the 3,000 M_E (where M_E is the mass of Earth) of HD 114762 in 1989, to the 150 M_E of 51 Peg in 1995, down to 1.1 M_E for the companion of α Centauri B in 2012 (ref. 33).

Ensemble properties of exoplanets

After the initial discovery phase, it became possible to derive unbiased exoplanet population statistics by quantifying detection efficiencies as a function of planet parameters (orbital period, mass and eccentricity). In this Review, we summarize the results of various attempts to characterize the ensemble properties of exoplanets using the radial-velocity technique. We complement these with an overview of the transit searches for hot Jupiters; these have also developed tremendously over the past decade. We restrict ourselves to ground-based surveys (see the Review by Lissauer *et al.* on page 336 for results of Kepler mission).

Statistics of gas-giant planets

Soon after the discovery of 51 Peg b, it became clear that short-period gas giants are relatively rare. Globally, early radial-velocity surveys mainly revealed a population of gas giants at orbital distances of 1–5 AU[34] (1 AU is the Sun–Earth distance). Key characteristics of this population include[35,36] an overall occurrence rate of about 15% (minimum mass $M\sin i > 50\ M_E$, orbital period $(P) < 10$ years); a mass distribution peaking at ~1–2 M_J with a 'brown dwarf desert' above 10–20 M_J; a wide distribution of orbital eccentricities that differs markedly from the low eccentricities seen in the Solar System; a higher metallicity of the host stars when compared with the average value found for their field star counterparts; and an overall occurrence rate of 1.05 ± 0.26% for hot Jupiters[35,37], valid for planets with $M\sin i > 0.1\ M_J$ and $P < 10$ days.

We note that our knowledge of the period distribution is at present limited by the duration of radial-velocity surveys and the sampling of long-period signals. We stress the importance of continuing these programmes for at least a decade to thoroughly probe the 5–10 AU region of planetary systems, where the formation of giant planets is likely to be most efficient. This is also the region where significant overlaps with direct imaging and microlensing techniques are expected.

In many cases, not one but several giant planets have been found in the same system[34,38]. Various types of dynamical configurations exist, from widely separated orbits to strongly interacting mean motion resonances[39]. Owing to the compactness and proximity of such resonances, the dynamical stability of several systems is not *a priori* obvious and must to be probed by dedicated numerical integrations. In favourable cases, planet–planet interactions are sufficiently strong to affect radial velocities in a measurable way (and on orbital timescales), which then yields direct constraints on the inclination angles of the orbits and true masses of the planets[40]. There are some notable examples illustrating the diversity of the population of giant planets (Table 1).

So far, perhaps the most striking result concerning long-period giant planets has been their tendency to have high orbital eccentricities (median value of about 0.3). The standard scenario of planet formation within a protoplanetary disk calls for orbits to be much closer to circular. The Solar System has long been seen as a prototypical example of this model. Clearly, the formation and evolution of planetary systems is generally much more complex than originally thought.

Strong gravitational interactions between giant planets after disk dissipation[41,42], as well as the gravitational influence of bound or passing stellar companions[43], probably have a crucial role in the evolution and the final shaping of planetary systems. In this context, a major question that has yet to be answered is how common Solar System analogues are; that is, systems whose dynamics are dominated by a massive gas giant on a low-eccentricity orbit at several astronomical units from the star.

Insights from ground-based transit searches

Soon after the discovery of the first transiting giant planet, HD 209458b[23,24], several ground-based efforts started to target the population of hot Jupiters through the photometric transit technique. Exoplanet transits mainly provide planetary orbital period, inclination and planet size (radius). Coupled with radial-velocity measurements, which provide the planetary mass, these can be used to derive the planet bulk density. This has been the main observational method to constrain the internal structure of exoplanets used so far.

Although early transit-search attempts were plagued by insufficient precision and inefficient operations, more recent large-scale surveys such as Wide Angle Search for Planets (WASP)[44] and Hungarian Automated Telescope Network (HATNet)[45] have eventually unveiled hundreds of transiting hot Jupiters orbiting FGK dwarfs within about 200 pc of the Sun. Two key properties of this population are a planet-size distribution that shows an excess of anomalously large radii, hinting at an as yet poorly understood physical mechanism that injects or traps excess internal heat inside the planet[46–50]; and the existence of a sub-population of hot Jupiters whose orbital plane is misaligned with respect to the stellar equatorial plane[51] (Fig. 2), preferentially found around hotter stars (with effective temperature ($T_{\rm eff}$) of more than 6,250 K)[52].

The formation and evolution of hot-Jupiter systems is a matter of active research and a full picture is still missing. For a long time the canonical scenario of inward migration within a protoplanetary disk prevailed, but the discovery of misaligned hot Jupiters has significantly changed this. It now seems clear that dynamical interactions between multiple giant planets, and/or interactions with massive outer companions (for example, Kozai oscillations), have a major role during or after planet formation[53–55]. This echoes the conclusions already drawn from the observed high eccentricities of longer-period giant planets. In those scenarios, planets are perturbed into orbits with high eccentricity and potentially high inclination. These are then circularized and realigned with the star through tidal interactions between the planet and the star. Indeed, the convergence between observed spin-orbit alignment and the existence of an outer stellar convection zone for cool stars ($T_{\rm eff} < 6{,}250$ K) points towards the influence of tides on the orbital evolution of at least some of the known hot Jupiters.

The rise of Neptunes and super-Earths

Improvements in radial-velocity precision towards 1 m s^{-1}, coupled with dedicated observing strategies, opened a new search space for radial-velocity surveys. In 2004, three planets in the Neptune-mass range were found for the first time: μ Arae c, GJ 436b and 55 Cnc e[56–58]. In 2006, HD 69830 was found to be the first system of multiple low-mass planets on close-in orbits, an architecture that would later prove to be common[59]. By 2008, it had become clear from the HARPS survey[32] that a large population of Neptunes and super-Earths exists on short-period orbits[60], with a preliminary occurrence rate of 30% for such planets ($M\sin i < 30\,M_{\rm E}$, $P < 50$ days). In 2011, early results from the space-based Kepler mission fully confirmed this picture and greatly expanded the landscape of small-planet studies[61]. (The Kepler results are discussed in the Review by Lissauer *et al.* on page 336.)

Only three radial-velocity programmes discovered a sufficient number of low-mass planets ($M\sin i < 30\,M_{\rm E}$) to allow meaningful statistical studies of this population. These are the HARPS survey for FGK stars (44 detections[32]), the HARPS survey of M dwarfs (10 detections[62]), and the Keck-HIRES survey of FGK stars (9 detections[63]). Key properties of the low-mass population unveiled by the HARPS surveys can be summarized as follows: for FGK stars, a global occurrence rate of 0.33 ± 0.05 planets per star for $M\sin i$ between 3 $M_{\rm E}$ and 30 $M_{\rm E}$ and $P < 50$ days; a mass distribution showing a steep rise below 20 $M_{\rm E}$, with a continuously rising trend at least down to 5 $M_{\rm E}$; a multiplicity rate of at least 70% among systems with at least one Neptune or super-Earth, that is, most low-mass planets are found in multi-planet systems; for M dwarfs, a global occurrence rate of 0.40 ± 0.11 planet per star for $M\sin i$ between 3 $M_{\rm E}$ and 30 $M_{\rm E}$ and $P < 50$ days; and an occurrence rate of super-Earths (1–10 $M_{\rm E}$) in the habitable zone of M dwarfs of $0.41^{+0.54}_{-0.13}$ planets per star.

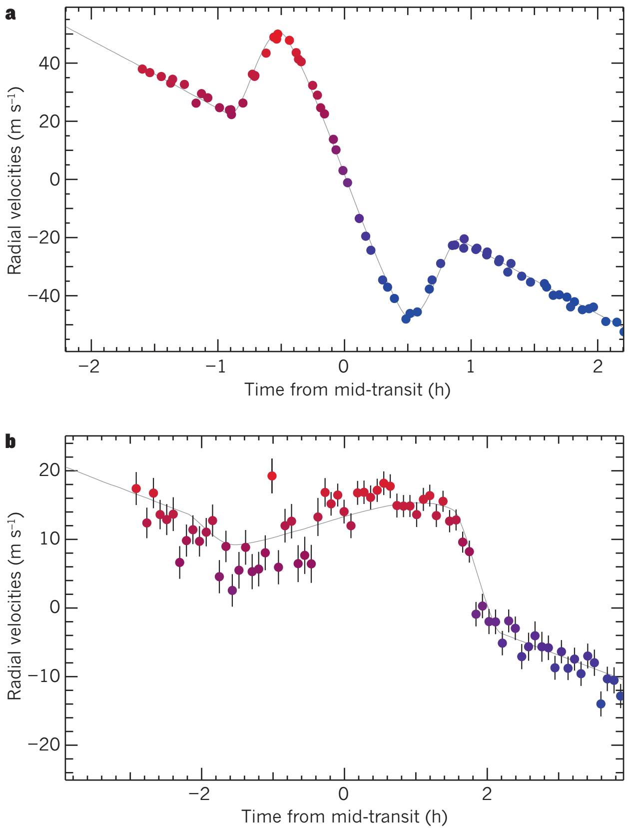

Figure 2 | Rossiter–McLaughlin effect for probing the spin-orbit alignment of exoplanets. For transiting exoplanets, precise radial-velocity measurements are not only able to measure exoplanet mass, but also the sky-projected angle between the planet's orbital plane and the stellar equatorial plane by the Rossiter–McLaughlin (RM) effect. The technique relies on the selective occultation of approaching and receeding parts of the rotating stellar disk by the planet during transit, causing variable net Doppler shifts that are detectable as deformations of the stellar spectral lines. The RM effect has a duration equal to the transit duration (typically hours) and is superimposed onto the usually larger radial-velocity signal caused by the gravitational pull of the planet on its star, which has periodicity equal to the planet orbital period (typically days for hot Jupiters). Two examples obtained with the HARPS spectrograph are shown. **a**, The exoplanet HD 189733A b exhibits a symmetric RM effect with a positive-then-negative radial-velocity anomaly that is the signature of an aligned and prograde star–planet system[116]. **b**, The WASP-8A system, however, shows a clearly asymmetric RM effect caused by a planet on a retrograde and strongly misaligned orbit with respect to the stellar rotation axis[114].

The high occurrence rates have one key consequence: systems of multiple planets with masses between 1 $M_{\rm E}$ and 20 $M_{\rm E}$ orbiting within 0.5–1.0 AU represent the most common type of planetary systems in the Galaxy. This result is supported by planet population synthesis models[11]. Moreover, such systems often exhibit a packed dynamical configuration, with little space left for stable orbits between consecutive planets (see Table 1 for examples of such compact systems). Planet formation and evolution scenarios must now account for the existence of this population. Competing theories include convergent migration of several protoplanets within a disk towards the inner regions of the system[64], and *in situ* formation of super-Earths or Neptunes within a disk that is significantly more massive than the Minimum Mass Solar Nebula[65].

Essential clues on the formation path of these planets will come from the study of their internal structure. A key question is whether volatiles (mainly water) are a significant constituent of the interiors, which would point to a formation beyond the ice line. Another open question is to what extent the prevalence of H/He envelopes is a function of planet mass, formation path and irradiation. These issues can be investigated by discovering super-Earths and Neptunes transiting nearby bright stars; a precise mass and radius can be obtained for these planets and atmospheric composition can be studied. At present, there are six such planets (55 Cnc e[58,66–68], HD 97658b[69,70], GJ 1214b[71], GJ 3470b[72], GJ 436b[57,73], and HAT-P-11b[74]) with radius (R) < 6 R_E, all of them discovered from the ground. The space missions CoRoT and Kepler have also provided a sample of objects with precisely-measured densities (see Review by Lissauer *et al.* on page 336). However, these targets are generally much more distant than those discovered by radial-velocity surveys, and therefore more difficult to characterize.

Although still limited, the sample of low-mass planets with well-measured densities already shows a wide diversity of compositions (Fig. 3 gives an overview of our present knowledge of Neptunes and super-Earth mean densities; see ref. 75 for densities obtained from the Kepler results and radial-velocity follow-up).

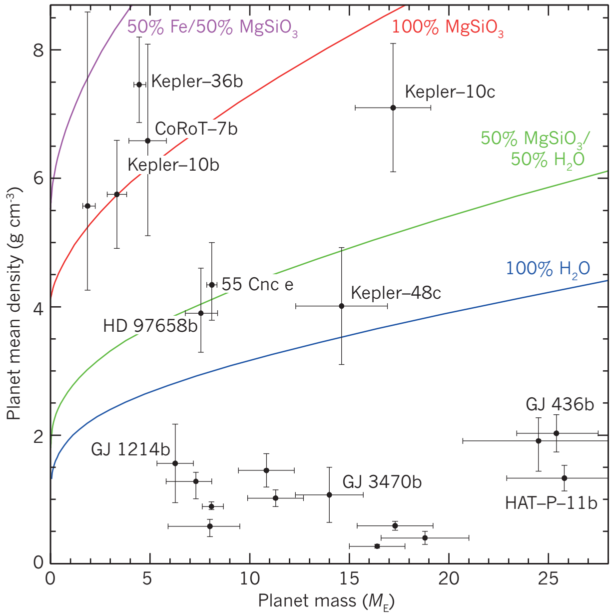

Figure 3 | Mass–density diagram for Neptunes and super-Earths. Few low-mass exoplanets have precise mass and radius measurements from which a reliable density can be derived. Here we show the mass and density of the 21 Neptunes and super-Earths that have a mass measurement with better than 20% precision. A population of low-density objects can be seen below around 2.0 g cm^{-3}, indicating a substantial H/He envelope much like Uranus and Neptune. Another population of much denser objects is also revealed, indicating bulk compositions ranging from terrestrial to more volatile-rich (for example, H_2O). The overall trend indicates lower densities towards higher masses. However, high-density objects seem to exist also at masses above 10 M_E, while low-density mini-Neptunes occur at masses of only a few Earth masses (M_E). The planets GJ 1214b, HD 97658b and 55 Cnc e span a narrow mass range of 6–8 M_E and have mean densities from 1.6 g cm^{-3} (GJ 1214b) to almost 5 g cm^{-3} (55 Cnc e), indicating very different internal structures at a given mass. This hints at a complex mass–radius relationship for low-mass exoplanets that does not depend on mass (or radius) alone, but also on environmental effects related to the formation and evolution of planetary systems. Mass–density relations from internal structure models with various bulk compositions are superimposed onto the observations[117]. For clarity, only a selection of the exoplanets are labelled.

Finally, radial-velocity surveys have recently come tantalizingly close to discovering planets in the habitable zone. The GJ 581 and HD 85512 systems comprise at least one super-Earth that could lie at the edge of habitability, depending on surface conditions[76,77]. Moreover, the planets GJ 667C c and HD 40307g are located within the classical habitable zone[78–80]. However, because neither the bulk density nor the atmospheric composition of these worlds is known, all discussions about their habitability remain largely speculative.

The discovery of such objects has been possible thanks to sub-metre-per-second radial-velocity precision and a careful analysis of the radial-velocity time series. At this level of precision, however, various physical phenomena in stellar photospheres contribute significant signals that can hide planetary radial-velocity signatures if not properly modelled. Solar-type stars have an outer convective envelope that exhibits variability on different timescales. Granulation, magnetic features (such as cool spots, plages and faculae) and long-term activity cycles all induce radial-velocity variability at the metre-per-second level[81,82]. Understanding how to diagnose and correct these effects is an active area of research[83–85]. State-of-the-art instrumentation and dense temporal sampling are the key to making progress in this field, and to ultimately push radial-velocity sensitivity down to the 10 cm s^{-1} level. This is the realm of habitable, Earth-mass planets around solar-type stars. Considering that HARPS has already detected planetary signals with an amplitude of 50 cm s^{-1} (ref. 32), and that modelling of stellar signals is still in its infancy, the exploration of the habitable zone around nearby FGK and M dwarfs is within reach of the radial-velocity technique. That is the main goal of future Doppler instruments (for example, the Echelle Spectrograph for Rocky Exoplanet and Stable Spectroscopic Observations (ESPRESSO) on the European Southern Observatory Very Large Telescope (ESO-VLT), see Review by Pepe *et al.* on page 358).

Chemical clues for stars with planets

One of the most crucial pieces of information to understand the properties of the discovered planets and to access their formation process comes from the study of planet host stars. On the one hand, precise stellar parameters, such as the radius, are crucial if we want to measure precise values for the radius of a transiting planet[86]. On the other hand, the chemical composition of a planet, both its interior and atmosphere, is also likely to be related to the chemical composition of the protostellar cloud, reflected in the composition of the stellar atmosphere[87]. The precise derivation of stellar chemical abundances thus provides important clues to understanding the planets and their observed properties.

Furthermore, a number of studies have pointed towards the existence of a strong relationship between the properties and frequency of the new-found planets and those of their host stars. Large spectroscopic studies[88,89] confirmed initial suspicions of a positive correlation between the probability of finding a giant planet and the metal content of the stars (Fig. 4). Curiously, this strong metallicity–giant-planet correlation was not found for the lowest mass planets[90,91].

It was soon realized that this correlation for giant planets was a key aspect of understanding planet formation. The simple existence of such a correlation has been pointed out as a strong evidence for giant-planet formation through the core-accretion process[11]. The lack of correlation for the lower-mass planets is also in full agreement with the expectations from such models. Indeed, stars formed out of metal-rich clouds are expected to have a higher mass of solid elements in their protoplanetary disks, thus leading to the formation of planet cores over a short timescale. These are then able to accrete gas and become giant planets. However, stars formed out of metal-poor clouds will not have much planet-forming material in their disks. The planets will grow slowly, never achieving enough mass to become giant planets.

Recent results from a specific survey for giant planets orbiting a sample of metal-poor stars was conducted with the Doppler velocimetry technique, using the HARPS spectrograph[12]. The results fully confirm the lower frequency of giant planets orbiting lower metallicity stars,

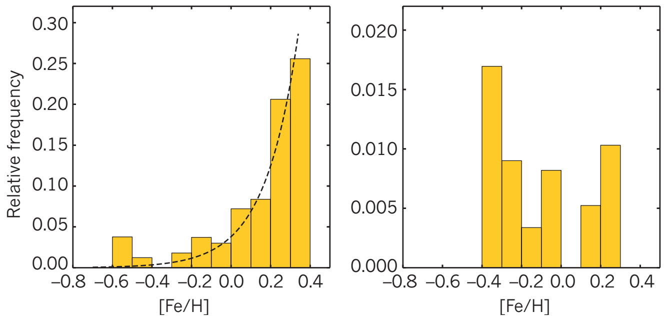

Figure 4 | Metallicity distribution of planet-hosting stars. In the left panel, the frequency of giant planets as a function of stellar metallicity is shown based on results from the HARPS planet search programme. The dashed line shows a power-law fit to the histogram values. In the right panel, we present the same plot but for stars that host only Neptune- or super-Earth-like planets. By metallicity we denote the abundance (A) of iron relative to the Sun, $[\mathrm{Fe/H}] = \log(A_{\mathrm{Fe}}/A_{\mathrm{H}})$ star $- \log(A_{\mathrm{Fe}}/A_{\mathrm{H}})$ Sun. These plots show a clear correlation between the presence of giant planets and the metallicity of the star. This trend is not seen for stars hosting lower-mass planets (as in ref. 90).

and point to a possible limit in metallicity, below which no giant planets may be formed.

Further evidence for the planet-formation process comes from the study of specific elemental abundances. It is now becoming clear that the abundance of α elements plays an important part in the formation of planetary systems, particularly in metal-poor environments[92]. The role of the abundances of other elements is also under discussion; some curious trends are a matter of strong debate, for example the abundances of the light element lithium[93,94], its isotope lithium-6 (refs 95, 96) or other elements[97,98].

It is important to note that the role of stellar metallicity in the formation of different architectures of planetary systems has also been addressed. Recently, suspicions have been raised concerning the influence of stellar metallicity on the orbital period of planets[99,100] — planets orbiting metal-poor stars have longer periods than those in metal-rich systems. These results show that metallicity is one of the most crucial ingredients in the formation of planetary systems, controlling not only the planet-formation efficiency, but also the outcome of the planet-formation process, including mass, composition and architecture.

Future prospects

How will the field be moved forward? Almost 20 years after the discovery of 51 Peg b, the field of exoplanets has reached maturity, but our knowledge remains patchy and exoplanet parameter space has not been explored systematically. Clearly, the future lies in the detection and full characterization of entire planetary systems around nearby bright stars, for which precision measurements of both the stellar and planetary parameters can be obtained. To this purpose, a wealth of ground-based and space-based facilities will be working together in a common effort.

The search for transits of super-Earths and Neptunes around bright stars will be carried out by the Next Generation Transit Search (NGTS, in 2014), the ongoing MEarth project and other ground-based surveys; and by the TESS (in 2017), Kepler-K2 (in 2014) and PLATO (by 2024) missions from space. PLATO in particular will detect transiting Earth-like planets in the habitable zone of nearby solar-type stars. At the same time, radial-velocity surveys using spectrographs such as HARPS, HARPS-N, Keck HIRES, Automated Planet Finder (APF) at Lick, ESPRESSO (to come into use in 2016), CARMENES (to begin work in 2015) and SPiROU (to begin in 2017) will continue the thorough exploration of planetary systems in the solar neighbourhood, and will carry out the follow-up of the above-mentioned transit search missions to measure planet masses. The CHEOPS mission (in 2017) will provide essential support to both radial-velocity and transit surveys through a flexible high-precision photometric follow-up from space. In addition, the European Space Agency's ongoing Gaia mission will provide high-accuracy fundamental stellar parameters for all planet host stars, and, coupled to high-resolution spectroscopy from the ground, will greatly improve the achievable precision of planetary masses and radii. Gaia will also detect giant planets at intermediate semi-major axes, complementing radial-velocity surveys and high-contrast imaging in an effort to fully explore planetary systems, including dynamically important gas giants on long-period orbits.

By between 2020 and 2025 the exoplanet landscape will, therefore, offer a tantalizing collection of objects spanning the whole parameter space and including terrestrial planets with habitable surface conditions. There is a clear path forward for finding the 'best' such planets — those that are closest to the Sun and most amenable to further characterization. Not only will their bulk composition be well constrained, but also their atmospheres will be probed with techniques such as transmission spectroscopy (primary transit) and emission spectroscopy (secondary eclipse). The James Webb Space Telescope (launching in 2018) will lead these efforts, complemented by high-resolution spectroscopy from the ground with the future extremely large telescopes. We are lucky enough to live in a time in which humans are, for the first time, contemplating the realistic possibility of exploring other planets similar to our own. Whether they will be few or plenty, orbiting a Sun-like star or an M dwarf, rocky or ocean worlds, with Earth-like atmospheres or more exotic ones, remains to be seen. This makes the quest all the more exciting. ■

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