Exoplanetary Science: An Overview

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Abstract Two decades ago, the first exoplanet was found orbiting a solar-type star. Since then, many surprising discoveries have been made. We now know that the architecture and properties of the Solar System's planets are more an exception than a rule. In this paper we review the main planet detection methods and present some of the most interesting discoveries as well as their connection to the study of planet-host stars.

1 Introduction

The number of known extrasolar planets is rising on an almost daily basis, with more than 3500 currently listed at The Extrasolar Planets Encyclopaedia[1] (Schneider et al. 2011). The impact of these discoveries is considerable, both scientifically and socially. They represent the first firm steps of humankind towards the detection and characterization of other planets similar to our Earth. This domain is opening new bridges between different fields in Astrophysics (e.g., stellar astrophysics, solar system research) and other areas of knowledge such as geophysics (e.g., Valencia et al. 2006) and biology (Kaltenegger and Sasselov 2011). Together these bring new hopes of finding an Earth-like planet where life may have evolved.

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[1] http://exoplanet.eu.

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The diversity of discovered planets is raising new questions and opening new pathways. The community presently agrees that planets, in particular rocky planets like our Earth, are very common around solar-type stars (FGK and M dwarfs; e.g., Udry et al. 2007; Howard et al. 2012; Mayor et al. 2014). This conclusion is fully supported by state-of-the-art planet formation models based on the core-accretion paradigm, that predict low-mass/small-radius planets to largely surmount the number of their Jovian or Neptune-like counterparts (Ida and Lin 2004; Mordasini et al. 2012).

While the number and variety of discovered planets are still important assets for exoplanet research (e.g., with an impact for the models), the focus of extrasolar planet researchers is now moving towards three main lines: (1) the detection of progressively lower-mass planets, with the goal of finding an Earth sibling, (2) the detailed characterization of known exoplanets, including their interior structures and atmospheres, and (3) the understanding of the planet formation processes, by comparing the properties of the detected worlds with expectations from theoretical models.

All these lines of research have already seen their own success. Radial-velocity (RV) and transit surveys have found an increasing number of low-mass/small-radius planets orbiting other suns (Borucki et al. 2011; Dumusque et al. 2012; Mayor et al. 2014). Some of these may even be in the habitable zone (Pepe et al. 2011; Quintana et al. 2014; Anglada-Escudé et al. 2016). The precision of the transit measurements, in combination with mass determinations from RV measurements and planet interior models, also allowed to determine the bulk composition of several planets (Léger et al. 2009; Howard 2013; Pepe et al. 2013). For the most favorable cases, exquisite measurements further allowed to detect both the emitted (infrared) and reflected (optical) light of exoplanets, as well as the presence of specific atmospheric lines (Brogi et al. 2012; Rodler et al. 2012; Martins et al. 2015). These measurements are providing a first insight into the physics of exoplanet atmospheres.

New hopes are now coming from new instruments, including ground-based optical spectrographs such as ESPRESSO (Pepe et al. 2014), capable of achieving down to sub-m/s precision in RV. A whole new generation of infrared (IR) spectrographs is also on its way, as well as a new optical and near-infrared (NIR) high-resolution spectrograph for ESO's E-ELT. To these we should add a whole new generation of ground- and space-based projects that will search and characterize transiting low-mass/small-radius planets. Many of these projects are meant to start operating in no more than 1 or 2 years, opening for the first time the possibility to address in a comprehensive way the detection and characterization of Earth-like planets orbiting nearby stars.

In this chapter we will briefly review some of the most relevant points inherent to exoplanet research. We will start by reviewing the main detection methods, their potential and limitations. The challenges imposed by astrophysical noise will then be presented, including the problems produced by stellar activity. We then briefly review the main results from exoplanet research. We will concentrate on the Doppler and transit methods, with a stronger accent on the former. The information provided by the analysis of the planet-host stars will further be discussed. We will conclude

with the prospects from future missions and projects in the field. More details can be found in the cited papers.

2 Planet Detection Methods

At a moment when thousands of planets are known, we may wonder that exoplanet detection has always been an easy task. However, we must be reminded that a long way has been covered from the early frustrating efforts using the astrometric methods (e.g., van de Kamp 1983) until the detection of the first exoplanet orbiting a solar-type star (51 Peg b; Mayor and Queloz 1995). The enthusiasm that followed this first detection precipitated the discovery of other worlds. The numbers slowly started rising, but in the end of the twentieth century only a dozen or so planets were known to orbit other solar-type stars.

The detection of the first transiting planet was only due 5 years after 51 Peg b (Charbonneau et al. 2000). This detection was not only the first allowing to derive the radius of an exoplanet, but also a confirmation that the "strange" hot Jupiters (short-period giant planets, previously not expected to exist based on planet formation models) were indeed planetary in nature (see below). The years that followed were of great success: planets with lower and lower masses were being found using the RV method (Butler et al. 2004; McArthur et al. 2004; Santos et al. 2004). Several transit surveys also started to provide the first results. But only in the last few years we could finally start probing in more detail the smaller mass/radius end of the planet population. This was largely due to the launch of the *Kepler* mission (Borucki et al. 2011) and to the improvement of the methods used to extract information from the radial-velocity data (e.g., Fischer et al. 2016).

Indeed, although the present day success of the exoplanet detection and characterization efforts is based on the development of a number of different techniques and methods, the radial-velocity and transit methods are certainly the most prolific so far. In this review we will thus concentrate on a basic description of the most used or successful methods, or those that will, from our perspective, be more fruitful in the years to come. In particular, we will focus on the radial-velocity, transit, and astrometric methods, as well as on a review of their stronger aspects and challenges. For more details and a description of other methods, we point the reader to some recent reviews (Seager et al. 2010; Perryman 2014) and to some of the chapters in this book.

2.1 Radial Velocities

The method behind the detection of the first exoplanet orbiting a solar-type star is the radial-velocity technique. This method is based on the detection of the stellar motion (or wobble) of the star around the center of mass of the star-planet system.

The velocity semi-amplitude expected for a star of mass M_1 orbited by a planet of mass M_2 can be shown to be:

$$K_1 = 212.9 \left(\frac{M_1}{P} \right)^{1/3} \frac{q}{(1+q)^{2/3}} \frac{\sin i}{\sqrt{1-e^2}} \quad \left[\text{km s}^{-1} \right] \, , \qquad (1)$$

where $q = M_2/M_1$, and i is the inclination of the orbital axis with respect to the line of sight. In this equation, the masses (M_1 and M_2) are expressed in solar masses, and the orbital period (P) in days (for details, see, e.g., Hilditch 2001). This equation shows that the higher the planet mass and the shorter the orbital period, the stronger will be the RV signal. RVs are thus more sensitive to short-period, massive planets. It is thus with no surprise that the first detected planets orbiting Sun-like stars were short-period giants, the so called hot Jupiters[2] (Mayor et al. 2014).

The RV of the star can be measured from the Doppler shift with high-resolution spectroscopic measurements, using the Doppler equation $\frac{\Delta\lambda}{\lambda} = \frac{v}{c}$, where c is the speed of light, λ is the reference wavelength (at zero velocity; typically the reference wavelength of an absorption spectral line), $\Delta\lambda$ is the wavelength shift observed, and v is the radial velocity. The biggest challenge of this technique is that one needs to measure the stellar velocity with a very high precision. In optical wavelengths these small amplitudes translate to values of $\Delta\lambda \sim 10^{-4}$Å. For comparison, a typical high-resolution spectrograph (with a resolution $R = \lambda/\Delta\lambda = 100,000$) is able to resolve two adjacent wavelengths separated by $\sim$0.1Å.

From Eq. (1) we can derive that the semi-amplitude K_1 of a star induced by the presence of a Jupiter-like planet (with a mass of $318\,M_\oplus$ and an orbital period of $\sim$12 years) is only $\sim$13 m/s, while for an Earth-like planet this value decreases to a mere $\sim$8 cm/s.

To circumvent the difficulties involved in the detection of such low-amplitude signals, two main aspects must be taken into account. First, the typical spectrum of a solar-type star has thousands of well-defined absorption lines. Using this information in a statistical way we will be able to achieve the necessary precision. But this is not enough if the spectrograph itself is not stable, or if we cannot control the instrument drifts as a function of time. An accurate way to measure and control the wavelength-to-pixel calibration is thus needed. This is usually achieved using the spectrum of a calibration lamp that is obtained simultaneously with the target spectrum (e.g., Baranne et al. 1996), or using a gas cell whose spectrum is superposed on the spectrum of our star (e.g., Campbell et al. 1988).

For reference, currently the most accurate RV instruments for planet searches are able to measure long-term RVs with a precision better than 1 m/s (for a review, see Fischer et al. 2016). Future instruments such as ESPRESSO, for the ESO-VLT, will achieve the 10 cm/s level, allowing to detect Earth-like planets in the habitable zones of solar-type stars.

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[2]Even if they are not the most prevalent kind of planets.

One immediate limitation of the RV technique is that we are only able to measure the projected radial velocity, i.e., the component of the radial-velocity in the direction of the line of sight. This implies that we can only estimate the "projected mass" of the companion responsible for the observed stellar wobble, i.e., its minimum mass ($M_2 \sin i$). Fortunately, it can be shown that for orbits randomly oriented in space it is much more likely to have $\sin i$ close to unity. This means that the minimum masses obtained are statistically very close to the real masses. The unambiguous determination of the true mass is, however, only possible if a value for the orbital inclination is obtained (e.g., through an astrometric detection or a transit measurement).

2.2 Photometric Transits

When a planet crosses the stellar disk as seen from us, it will occult part of it. This phenomenon, called a transit, can be observed if the orbital axis of the planet is closely perpendicular to our line of sight. For a given system, we can compute that the geometric probability (p) that a full transit will occur can be expressed by (to a good approximation):

$$p = \frac{R_{\text{star}}}{a},\qquad(2)$$

where R_{star} and a are the stellar and orbital radius, respectively. This formula is valid for the case of a circular orbit. From this equation we can see that the transit technique is more sensitive to short-period planets. While for a 3-day orbit hot Jupiter p is close to 10%, for a planet at 1 AU from its parent star (orbital period close to 1 year) p goes down to only 0.5%.

If a transit event is observed, the expected luminosity variation can be derived to be of the order of:

$$\frac{\Delta L}{L} = \left(\frac{R_{\text{planet}}}{R_{\text{star}}}\right)^2.\qquad(3)$$

For a Jupiter-like planet, $R_{\text{planet}} \sim 0.1\, R_{\text{star}}$, inducing thus a photometric variation of the order of 1%. A value of the order of 100 parts per million (ppm) is expected for an Earth-radius object. Large planets around small stars are thus easier to detect using the transit method.

Transits have shown to be an excellent way to detect planets orbiting other stars. At first used to complement the detections of radial-velocity planets (e.g., Charbonneau et al. 2000), large ground- and space-based surveys like WASP, HAT, *CoRoT* and *Kepler* revealed the presence of thousands of candidates, some with radii smaller than that of Earth. However, one point that is clear from above is the fact that the transit method only provides information about the radius of the planet

(provided that the stellar radius is known). Except in a few cases where multi-planet systems are detected and, e.g., planet-planet interactions are strong (e.g., Ford et al. 2012), there is no information on the planet mass.

In other words, given the large diversity of planet densities already discovered, if we want to characterize the planet in more detail, we need to use a method (e.g., radial velocities) that enables us to derive the planet mass. Having both radius and mass allows one to estimate the planet density, and thus have a first idea about the planetary composition. Further to this, it is well known that different "non-planetary" phenomena can produce signals that almost perfectly mimic a photometric transit. These are responsible for the large false positive rates that affect especially the higher-mass planets (Santerne et al. 2016). Complementary observations are thus usually needed once a transit signature is detected, even if a statistical confirmation is done (Torres et al. 2011; Díaz et al. 2014).

2.3 Astrometry

Astronomers have long tried to use the dynamical effect that a planet has on the stellar motion to measure the small astrometric periodic shift of a star as it moves about the center of mass of the star-planet system. The astrometric detection of an extrasolar planet can be described, in a very basic approach, by simple physics. The semi-major axis of the orbital motion of a star around the center of mass of a two-body system can be described by:

$$M_1 \, a_1 = M_2 \, a_2 \,, \tag{4}$$

where M_1 and M_2 are the masses of the two bodies, and a_1 and a_2 the semi-major axes of their orbits. The distance $a = a_1 + a_2$ (the semi-major axis of the relative orbit) is also related to the orbital period P through Kepler's third law,

$$P^2 = \frac{a^3}{M_1 + M_2} \,. \tag{5}$$

In principle, if we measure a_1, a_2, and P, we can solve the system above and derive the mass of the two bodies. This is the case for some visual binary stars. In practice, the measurement of the astrometric motion of the star in a star-planet system is far more complex. For instance, we can only hope to measure a_1 and the period P, since we are not able to directly observe the planet. To solve the above system we need, for example, to estimate the mass of the star (M_1) using stellar evolution models.

Given the small expected astrometric motions[3] (of the order of 1 microarcsecond for the best cases), current technology still did not allow to unambiguously detect from scratch a planet orbiting another star using the astrometric method. The only existing detections are of planets or brown dwarfs firstly detected using the radial-velocity technique (e.g., Benedict et al. 2006). More hopes come from the analysis of data from the ESA *Gaia* mission, whose exquisite astrometric precision is expected to allow the detection of thousands of giant planets (Sozzetti et al. 2001).

As we can see from Eqs. (4) and (5), the semi-major axis of the astrometric motion of the star around the center of mass of the star-planet system is proportional both to the mass of the companion and to its orbital period. This means that the astrometric technique is most sensitive to long-period companions. This makes this method complementary to the radial-velocity technique. Similarly to the latter, however, it is mostly sensitive to the detection of planets around lower-mass stars.

3 Challenges

Adding to the technical challenges mentioned above, the detection and characterization of other planets also has to deal with the "noise" induced by different astrophysical sources. Phenomena related to stellar activity, stellar granulation, and oscillations are particularly nasty for exoplanet detection and characterization efforts using the radial-velocity method. They can prevent us from finding planets, if the perturbation is larger than the orbital RV variation, or even give us false candidates, if they produce a periodic and stable signal over a few rotational periods (e.g., Figueira et al. 2010). Furthermore, these physical phenomena produce signals with different timescales: from several years (related with the long-term magnetic cycles; Santos et al. 2010) down to a few minutes (the oscillation modes of stars, that allow one to apply asteroseismic methods to probe the stellar interiors; Dumusque et al. 2011).

The acoustic modes of solar-type stars as well as the atmospheric granulation motions can induce RV amplitudes of the order of a few m/s. To circumvent this effect, long exposures (longer than the timescale of the oscillation modes) are usually taken to average out the solar-type acoustic modes. These modes have typical periods of the order of 5 min in a solar-type star. The granulation noise has longer timescales (from hours to a few days), that are more difficult to handle. Specific observational strategies are often used to minimize the problem (e.g., Dumusque et al. 2012).

The phenomena related to stellar activity, induced by strong magnetic fields in the stellar surface (e.g., spots, faculae, convective changes), also strongly affect both the photometric and RV signals, in timescales typical of the rotational period of the

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[3]For example, a Jupiter-like planet in a 10-year orbit around a solar-mass star located 10 pc away from us, induces an astrometric motion of only 440 microarcseconds.

star. In RVs, measurements of different activity indicators, such as line asymmetries, through bisector analysis (e.g., Queloz et al. 2001) are often used to diagnose these effects. However, recent examples show that the effects of stellar activity features are not fully understood, leading to signals that almost perfectly mimic the signature of planets (even for non-active stars; Santos et al. 2014). Recent developments of data analysis techniques promise to solve part of these problems (e.g., Faria et al. 2016).

Stellar activity is also particularly relevant when dealing with transit searches. Not only it induces strong photometric modulations (that need to be filtered), but also they induce in-transit fluctuations that prevent us from having precise values for the transit depth, and hence the planet radius (e.g., Oshagh et al. 2013). More details about these and other effects are discussed in the chapter by M. Oshagh in this book.

In brief, different sources of noise are a strong challenge in planet detection and characterization efforts. The understanding of the different physical phenomena as well as ways to model or subtract them are now one of the most important avenues to guarantee the success of future ground- and space-based exoplanet projects.

4   Population Statistics

The explosion of exoplanet discoveries in the 1990s was soon followed by studies of the overall population of exoplanets. These studies rely on dedicated surveys that allow for the detection efficiencies to be quantified as a function of planet parameters such as orbital period, mass and eccentricity. In this section we summarize the main results of the ensemble study of the planet population, focusing on radial-velocity surveys.

The minimum masses and orbital periods of the known exoplanets detected with radial velocities are shown in Fig. 1. We can identify three main groups: massive giant planets at short and long periods, and lower-mass planets at short periods.

4.1   Gas-Giant Planets

51 Peg b (Mayor and Queloz 1995) and other short-period planets discovered soon after (e.g., Butler et al. 1997) were the first examples of a new family of planets with circular orbits, Jupiter-like masses, and orbital periods less than 10 days (upper left quadrant of Fig. 1). These so-called *hot Jupiters* are now known to be relatively rare, with an occurrence rate close to 1% (Marcy et al. 2005; Mayor et al. 2011; Wright et al. 2012), but the fact that they exist as well as their orbital properties provide important clues to their formation process (e.g., Batygin et al. 2016; and references therein).

Radial-velocity surveys also revealed a population of gas giants at orbital distances between 1 and 5 AU (upper right quadrant of Fig. 1) with an overall
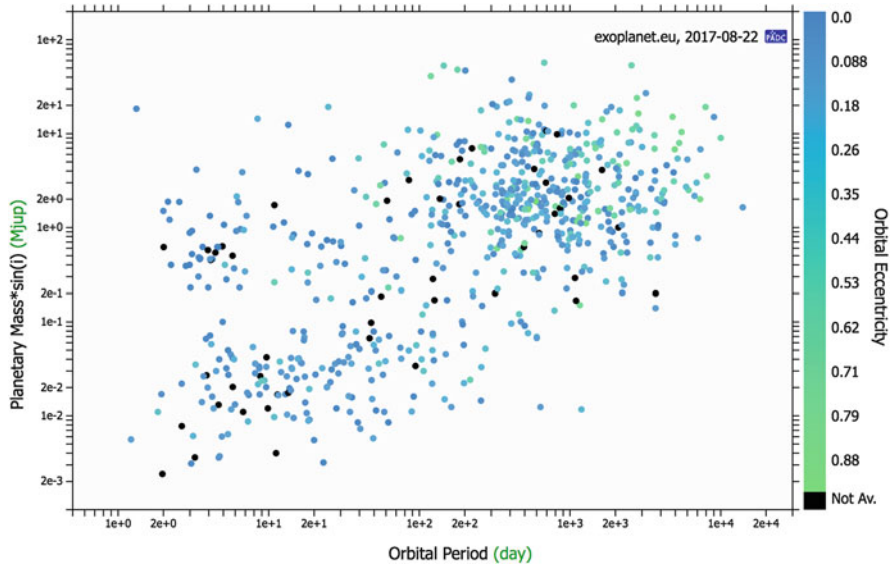
Fig. 1 Distribution of periods and minimum masses for the extrasolar planets detected with the radial-velocity method. The color code reflects the eccentricity of each planet. Obtained from http://exoplanet.eu

occurrence rate of about 15% for minimum masses larger than 50 $M_\oplus$ (0.15 M_{Jup}) and orbital periods less than 10 years (e.g., Udry and Santos 2007).

The mass distribution of the giant planets is shown in Fig. 2. The distribution peaks around 1–2 M_{Jup} and presents a long tail toward masses larger than 10 M_{Jup}. Within the brown-dwarf regime (masses between $\sim$15 M_{Jup} and $\sim$60 M_{Jup}) the number of detections is very small, in what has been called the "brown-dwarf desert". The number of objects with larger masses (stars) then rises again (not shown in Fig. 2). The bimodality of this mass distribution is taken as evidence of different formation mechanisms for stellar binaries and planetary systems (Sahlmann et al. 2010).

The population of giant planets shows a wide distribution of orbital eccentricities (noticeable in Fig. 1), unlike the low eccentricities seen in the Solar System. The eccentricity distribution is closer to that of binary stars (Udry and Santos 2007; their Fig. 6). This can be a signature of planet-planet scattering or interactions with bound or passing stellar companions. Many giant planets are also found in systems with various dynamical configurations (e.g., Correia et al. 2009; Wright et al. 2009). In some multi-planet systems, the gravitational interactions between planets are strong enough to be detectable in radial-velocity measurements, allowing for the orbital inclination angles and the true masses of the planets to be measured (e.g., Correia et al. 2010).
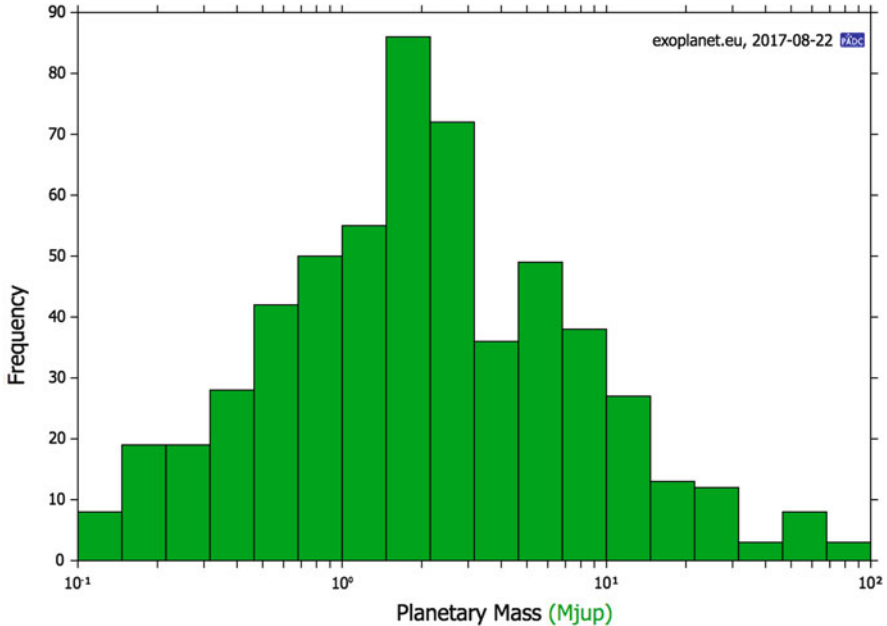
Fig. 2 Mass distribution of the population of giant planets detected with the RV method. Obtained from http://exoplanet.eu

4.2 Neptunes and Super-Earths

Some radial-velocity instruments, such as HARPS (Mayor et al. 2003; Lovis et al. 2006) or APF (Vogt et al. 2014), were built to achieve consistent precisions of 1 m/s. This opens the possibility for RV surveys to search for lower-mass planets. But since the detection of low-mass planets requires a large observational effort, only a few surveys gathered enough detections to allow for statistical studies. Results from the HARPS survey of FGK stars (Mayor et al. 2011), the HARPS survey of M dwarfs (Bonfils et al. 2013), and the HIRES survey of FGK stars (Howard et al. 2010), suggest a large population of Neptunes and super-Earths in short-period orbits. The occurrence rate of these planets, with $M \sin i < 30 M_\oplus$ and $P < 50$ days, is about 30% around FGK stars and 40% around M dwarfs.

The left panel of Fig. 3 shows the mass distribution of the planets detected in the HARPS survey (Mayor et al. 2011). After correcting the distribution for the detection biases (red histogram), we clearly see the importance of the population of low-mass planets, with a strong decrease of the number of planets between a few Earth masses and about $40 M_\oplus$. Planet population synthesis models (e.g., Mordasini et al. 2009) predicted these features of the mass distribution to be detectable when the RV measurement precision reached 1 m/s (see Fig. 3, right panel).

The high occurrence rates tell us that systems of multiple planets with masses between $1 M_\oplus$ and $20 M_\oplus$, orbiting within 0.5–1 AU, are the most common type of
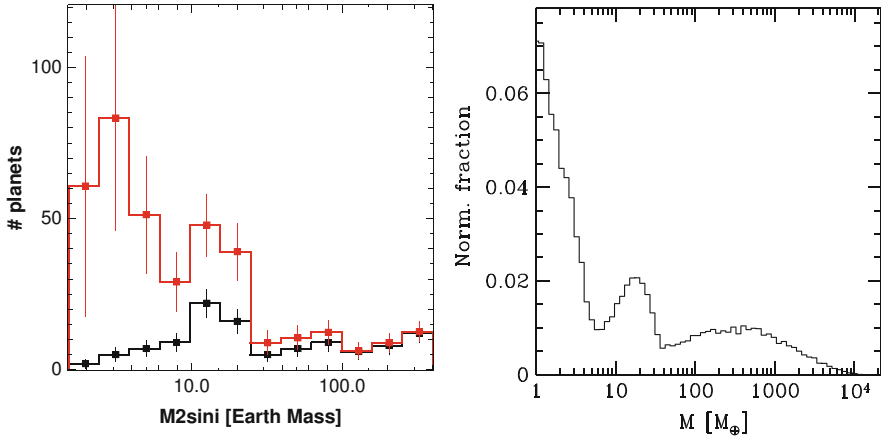
Fig. 3 *Left:* Planetary mass distributions from the HARPS planet survey, before (*black*) and after (*red*) correction for the detection bias (from Mayor et al. 2011). *Right:* Planetary initial mass function from a population synthesis model (from Mordasini et al. 2009)

planetary systems in the Galaxy. This remarkable result has been confirmed with transit surveys (see, e.g., Lissauer et al. 2014) and is in agreement with planet population synthesis models (Ida and Lin 2004; Mordasini et al. 2012, 2015).

4.3 Benchmark Planetary Systems

From the pool of exoplanet discoveries, a few systems have intrinsic interest as historical landmarks or as examples of the diversity of planetary properties. We briefly describe three such discoveries, which also showcase the interplay between the transit and radial-velocity methods.

Kepler-78 Kepler-78b was found transiting its G-type host star, with an unusually short orbital period of just 8.5 h (Sanchis-Ojeda et al. 2013). Radial-velocity follow-up observations provided, for the first time, a mass measurement for an Earth-sized planet (Pepe et al. 2013). The planet has a radius of $1.16\,R_\oplus$ and a mass of $1.86\,M_\oplus$, resulting in a density $5.57\,\mathrm{g\,cm^{-3}}$, which is similar to that of the Earth ($5.51\,\mathrm{g\,cm^{-3}}$). This suggests that Kepler-78b is also made primarily of rock and iron. This is one of many examples where combined RV and photometric observations provide strong constraints on the internal constitution of the planets.

Even though Kepler-78 is an active star, the RV detection was possible because of the short orbital period. The separation between activity-induced and planetary signals is much easier when the orbital period of the planet is much smaller than the rotation period of the star (e.g., Hatzes 2014).

HD 10180 Lovis et al. (2011) reported on the discovery of one of the most populated exoplanet systems known to date. Up to seven planets were found orbiting the solar-type star HD 10180 (but see Tuomi 2012; who find evidence for nine planets). This system is interesting because of its complex orbital configuration, showing significant secular interactions but no mean-motion resonances.

By the time this system was discovered, it became clear that several low-mass planetary systems exhibit a "packed" orbital architecture with little or no (dynamical) space left for additional planets. These architectures can be interpreted as the signature of planet formation scenarios in which type-I migration plays a major role.

GJ 667C Located at about 22 light years away in the constellation of Scorpius, GJ 667C is the smallest member of its triple star system. This star is an M1.5V red dwarf with an estimated mass of 0.33 times that of the Sun. The discovery history of the planetary system orbiting GJ 667C is complicated (Anglada-Escudé et al. 2012, 2013; Bonfils et al. 2013; Delfosse et al. 2013), mainly because of the presence of a few candidate planets orbiting well inside the habitable zone. Some of these planets have since been put into question (Feroz and Hobson 2014; Robertson and Mahadevan 2014) as being due to the magnetic activity of the star. Finding exoplanets in the habitable zones of M dwarfs is easier than in solar-type stars, but the rotation periods are also closer to the orbital periods of such planets. Additional data for this star and more refined analysis techniques are required to definitively explain the observed variations in the radial velocity of GJ 667C.

5   Know the Stars, Know the Planets

The study of planet-host stars is paramount to the understanding of the properties and formation mechanisms of exoplanets. For example, when a planet is found transiting, the measurement precision on the planetary radius depends directly on a precise knowledge of the stellar radius (cf. Sect. 2.2; see also Torres et al. 2008; Mortier et al. 2013) In addition, the chemical compositions of the planet (both interior and atmospheric), the protostellar disk and the stellar atmosphere are linked. Therefore, precise stellar chemical abundances can provide important clues in understanding the planets and their observed properties.

The metallicity-giant planet correlation is one example of this connection: it is one of the most striking and best established results for the population of giant planets that their host stars have a higher average metallicity when compared with field stars (e.g., Gonzalez 1997; Santos et al. 2001; Fischer and Valenti 2005). The clear correlation between the presence of giant planets and metallicity is visible in the left panel of Fig. 4. This correlation is key in constraining the planet formation process and its existence provides strong evidence for core-accretion being the main process of formation of giant planets. In protoplanetary disks with higher metallicity, rocky or icy cores are able to form in time for runaway accretion before
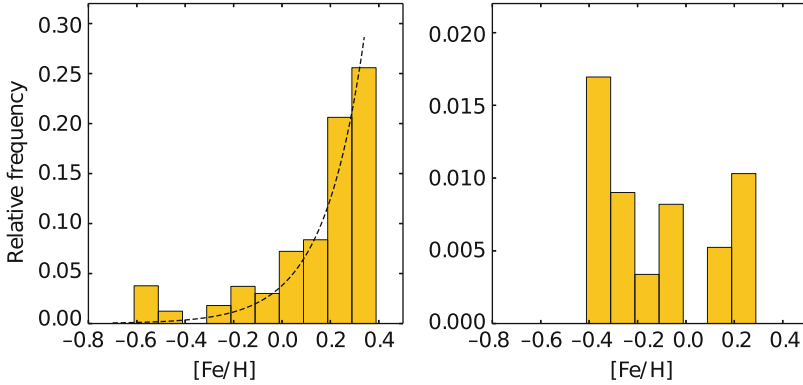
Fig. 4 The metallicity distribution of stars hosting giant planets (*left*) and Neptunes or super-Earths (*right*). There is a clear correlation between the presence of giant planets and the metallicity of the star, but this trend is not present for stars hosting lower-mass planets (Sousa et al. 2011). Adapted from Mayor et al. (2014)

disk dissipation occurs, while in lower-metallicity disks the cores do not grow fast enough to accrete gas in large quantities before disk dissipation, which results in a lower fraction of giant planets (Mordasini et al. 2009).

For the lower-mass planets (Fig. 4, right panel), there is no strong metallicity dependence of the occurrence rate (Sousa et al. 2011), indicating that these planets can form around stars with a wide range of metallicities (Buchhave et al. 2012). However, more recent results suggest that Neptunes (between 10 and 40 $M_\oplus$) may indeed show a (weak) metallicity correlation, while super-Earths ($< 10\,M_\oplus$) do not (Adibekyan et al. 2012; Courcol et al. 2016; Mulders et al. 2016).

The study of specific elemental abundances gives further insight into the planet-formation process. The abundance of α elements, for example, plays an important role in the formation of planetary systems, especially in metal-poor environments (Adibekyan et al. 2012). Abundances of other chemical elements, such as lithium (Reddy et al. 2002; Israelian et al. 2009; Baumann et al. 2010) and refractory elements, are also possible signatures of planet engulfment or terrestrial planet formation (González Hernández et al. 2010; Ramírez et al. 2010).

Stellar metallicity also plays an important role in the architectures of planetary systems: planets around metal-poor stars show longer periods and lower eccentricities than those with metal-rich hosts (Adibekyan et al. 2013; Dawson and Murray-Clay 2013). These trends point to the importance of planet-disk interaction and orbital migration, and provide constraints for the models and numerical simulations of planet formation and evolution.

6 A Bright Future Ahead

The diversity of exoplanet worlds is overwhelming. What else can the future bring? In the next few years we will have access to an array of instruments that will allow the study of entire planetary systems around nearby bright stars. This will mean precise measurements of both stellar and planetary parameters, from a combination of different observational techniques.

The legacy of *Kepler* in the search for transits of small planets will be in the hands of the Next Generation Transit Search (NGTS; Wheatley et al. 2013), the MEarth project (Irwin et al. 2009), and the *TESS* (Ricker et al. 2016), *CHEOPS* (Broeg et al. 2013) and *PLATO* (Rauer et al. 2014) space missions.

Radial-velocity surveys will continue to explore planetary systems in the solar neighborhood, with high-precision spectrographs like HARPS, HARPS-N, HIRES and APF. The cm/s level is now on sight with ESPRESSO (Pepe et al. 2014), and the NIR domain is open for exploration with CARMENES/Calar Alto (Quirrenbach et al. 2010), SPiROU/CFHT (Artigau et al. 2014), HPF/HET (Mahadevan et al. 2010) and GIANO/TNG (Oliva et al. 2004). Follow-up of transit detections with these instruments will provide precise densities and internal compositions for a large number of planets.

The *Gaia* mission already started delivering high-accuracy fundamental stellar parameters for all of the planet-host stars (Lindegren et al. 2016) and will also detect giant planets at intermediate semi-major axes. The *James Webb Space Telescope* (Gardner et al. 2006) and the future ground-based extremely large telescopes will study the atmospheric composition of the planets with both transmission and emission spectroscopy.

In summary, the instrumentation of the next few years will answer many of the most important questions about exoplanets. Many other new surprises will come as new discoveries arise. No one can tell with certainty if one of these instruments or missions will not discover the first Earth orbiting another Sun.

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