Solar system and Exoplanets

François Mignard and Alejandra Rrecio-Blanco during the conference dinner.

https://doi.org/10.1017/S1743921317006421 Published online by Cambridge University Press

Astronomy and Astrophysics in the Gaia sky
Proceedings IAU Symposium No. 330, 2017
A. Recio-Blanco, P. de Laverny, A.G.A. Brown & T. Prusti, eds.

doi:10.1017/S1743921317006421

Characterisation of exoplanet host stars: A window into planet formation

Nuno C. Santos[1,2]

[1]Instituto de Astrofísica e Ciências do Espaço, Universidade do Porto, CAUP, Rua das Estrelas, 4150-762 Porto, Portugal
email: nuno.santos@astro.up.pt

[2]Departamento de Física e Astronomia, Faculdade de Ciências, Universidade do Porto, Rua do Campo Alegre, 4169-007 Porto, Portugal

Abstract. The detection of thousands of planets orbiting stars other than the Sun has shown that planets are common throughout the Galaxy. However, the diversity of systems found has also raised many questions regarding the process of planet formation and evolution. Interestingly, but perhaps not unexpectedly, crucial information to constraint the planet formation models comes from the analysis of the planet-host stars. In this talk I will review why it is so important to study and understand the stars when finding and characterising exoplanets. I will then present some of the most relevant star-planet relations found to date, and how they are helping us to understand planet formation and evolution. I will end with a presentation of the future steps in this field, including what Gaia will bring to help constrain the properties of planet-host stars, as well as to the star-planet connection.

Keywords. planetary systems, stars: abundances, planetary systems: formation

1. Introduction

Since the detection of a giant planet orbiting the solar-type star 51 Peg Mayor & Queloz (1995) more than 3500 extrasolar planets have been published†. The impact of these discoveries is considerable, both scientifically and socially. They represent the first firm steps of humankind towards the detection and characterisation of other planets similar to our Earth. In this process, this multi-disciplinary 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 (Valencia *et al.* 2006) and biology (Kaltenegger *et al.* 2010). Together these bring new hopes of finding an Earth-like planet where life may have evolved.

The diversity of discovered planets is raising new questions and opening new pathways. One point is already clear, however: even though the precise frequency of the different kinds of planets in the Galaxy is a matter of debate, the community presently agrees that planets, in particular rocky planets like our Earth, are very common around solar type FGK and M stars (see e.g. Udry & Santos 2007, Howard *et al.* 2012, Bonfils *et al.* 2013). This conclusion is fully supported by state-of-the-art planet formation models based on the core-accretion paradigm, that further predict low mass/radius planets to largely surmount the number of their jovian or neptune-like counterparts (e.g. Mordasini *et al.* 2012).

The strong progress in this field is well illustrated by Fig. 1, where we plot, in the left panel, a mass-period diagram of the discovered exoplanets. The plot illustrates not only the large diversity of discovered planets, but also the clustering of planets around three

† For an up-to-date list see http://exoplanet.eu

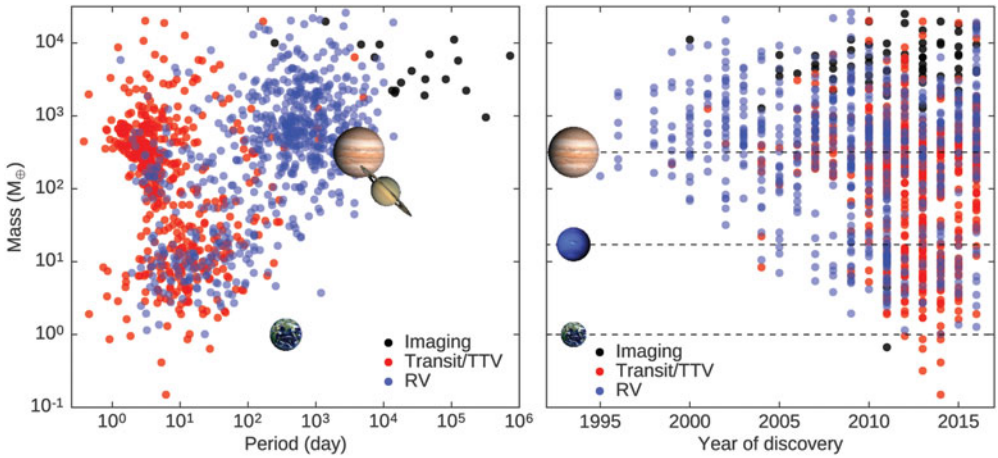

Figure 1. *Left*: Mass-period diagram for known exoplanets with a mass determination. Solar system planets Jupiter, Saturn, and the Earth are illustrated for reference. *Right*: Planet mass as a function of year of discovery. Solar system planets Jupiter, Neptune, and the Earth are illustrated for reference. From Adibekyan (2017).

main regions: the short period giant planets, also dubbed hot jupiters, occupy the upper-left part of the plot. Cool and temperate giants (more similar to Jupiter and Saturn) occupy the upper right part of the plot. Finally, the lower part of the diagram is populated by an increasing population of rocky and neptune-like planets. This latter population, though not the most represented in the plot (because its also the most difficult to detect), is likely the most common. In the right panel of this figure we also show the exoplanet mass as a function of the year of discovery, a plot that illustrates the progress in exoplanet discoveries and in the techniques used to detect them.

While the number and variety of discovered planets is still an important asset for exoplanet research (e.g. with an impact for the models), the focus of extrasolar planet researchers is now moving towards two main lines: i) the detection of lower and lower mass planets, with the goal of finding an Earth sibling, and ii) the detailed characterisation of known exoplanets, including their interior structures and atmospheres. Both lines of research have already seen their own success. Though it is out of the scope of the present paper to review in detail these results, we would like to point the reader to the recent reviews by Mayor *et al.* (2014), Fortney *et al.* (2014), and Burrows (2014).

Inherent to the detection and characterisation of exoplanets is the study of their host stars. In most cases, planet search and characterisation methods† only observe the star, not the planet itself. Phenomena related to stellar activity, stellar granulation, and oscillations (that act in different timescales) are particularly nasty for exoplanet detection and characterisation efforts using the radial velocity method (see e.g. Dumusque *et al.* 2011). They can prevent us from finding planets, if the perturbation is larger than the planet induced signal, 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). 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). In brief, different sources of noise are a strong

† Namely the radial velocity and transit methods, responsible for the discovery of the huge majority of the known exoplanets.

challenge in planet detection and characterisation efforts. The understanding of the different physical phenomena as well as ways to model or subtract them is now one of the most important avenues to guarantee the success of future ground- and space-based exoplanet projects.

A precise derivation of the physical characteristics of exoplanets is also intimately connected to our ability to derive the stellar properties. For example, when a planet is found transiting, the measurement precision on the planetary radius depends directly on the precise knowledge of the stellar radius (e.g. Torres *et al.* 2008, Mortier *et al.* 2013a). The stellar mass is also a key ingredient for the derivation of planet masses using the radial velocity method. The age of a planet can also only be known through the derivation of the stellar age. All these ingredients, together with the stellar irradiation (that depends also in the orbital distance) are fundamental to understand the potential for habitability.

Finally, it has been shown that the chemical composition of the stars is intimately connected to the frequency, architecture, and chemical composition of the discovered planets. This is likely not unexpected, since planets are formed in proto-planetary disks, being thus one of the outcomes of the star formation process. This review will concentrate on this aspect, namely by presenting and discussing some of the most relevant aspects of the star-planet connection. In Sect. 2 we will discuss the relation between stellar abundances and planet frequency. In Sect. 3 we will then see how stellar properties relate with the architecture of the discovered exoplanet systems and the chemical composition of the planets themselves. Finally, in Sect.4 we will present the future prospects in this research, not forgetting the role of Gaia.

2. Stellar abundances and planet frequency

A number of different studies pointed the existence of a strong relation between the properties and frequency of the newfound planets and those of their host stars. In this respect, the well known correlation between the stellar metallicity and the frequency of giant planets is a good example. Large spectroscopic studies (e.g. Santos *et al.* 2001, Santos *et al.* 2004, Fischer & Valenti 2005, Sousa *et al.* 2011) confirmed the initial suspicions of a positive correlation between the probability of finding a giant planet and the metal content of the stars (See Fig. 2). Curiously, this strong metallicity-giant planet correlation was not found for the lowest mass planets (Sousa *et al.* 2011, Buchhave *et al.* 2012). Both results, however, are in full agreement with the expectations from the most recent models of planet formation based on the core-accretion paradigm (e.g. e.g. Mordasini *et al.* 2012, and discussion therein). We should add, however, that recent results seem to suggest that the overall metal content of the stars may still be relevant for the formation of the lower mass planets (Zhu *et al.* 2016, Wang & Fischer 2015). The higher abundances of alpha elements in metal-poor planet hosts also points in that direction (Adibekyan *et al.* 2013).

Interestingly, recent results also suggest that on the other mass limit, planet formation may follow a different path. Santos *et al.* (2017) have shown that stars hosting planets with mass above $\sim 4\,M_{Jup}$ are metal poor when compared with stars hosting lower mass, giant planets (Fig. 3), a result that was shown to be statistically significant. This result suggests that above $\sim 4\,M_{Jup}$ giant planets may be mainly formed via a different physical process, likely a disk instability mechanism (e.g. Cai *et al.* 2006).

Its important to add that these results have only been possible thanks to the increase in the number of discovered planets, but also due to the existence of precise and uniform

https://doi.org/10.1017/S1743921317006421 Published online by Cambridge University Press

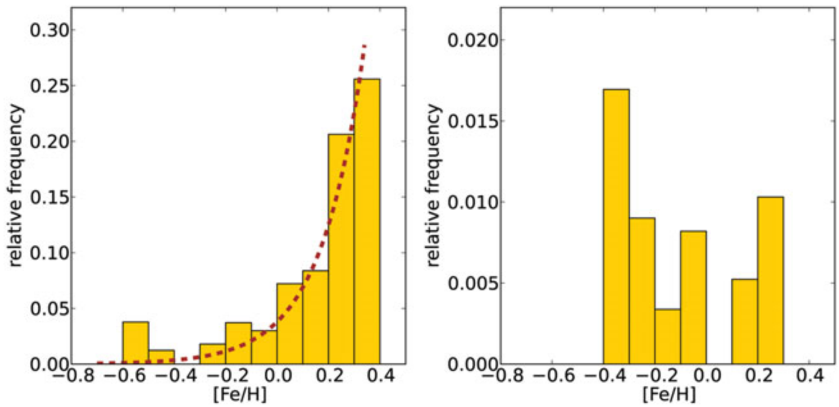

Figure 2. Frequency of giant (left panel) and neptune-mass (right panel) planets detected by radial velocity surveys as function of stellar metallicity (Sousa *et al.* 2011). From Mayor *et al.* (2014).

values for the stellar parameters and metallicities for planet host stars, such as the ones compiled in the SWEET-Cat database (Santos *et al.* 2013, Andreassen *et al.* 2017).

Although the general metallicity-giant planet correlation is reasonably well established, many details are still missing that may hold the clue to new and important details concerning planet formation. For example, the exact shape of the metallicity-planet correlation is still debated (Udry & Santos 2007, Johnson *et al.* 2010, Mortier *et al.* 2013b). The understanding of this issue may be critical to point out the mechanisms responsible for the formation of giant planets across the whole metallicity range (Matsuo *et al.* 2007), or to the understanding of the frequency of planets in the MilkyWay. The role of the abundances of other elements is also being discussed, with some curious trends being a strong matter of debate concerning e.g. the abundances of the light element lithium (e.g. Israelian *et al.* 2009, Baumann *et al.* 2010, Figueira *et al.* 2014).

It is worth adding that a role in the formation of giant planets has also been assigned to stellar mass. It is now widely accepted that the frequency of giant planets orbiting M dwarfs is considerably lower than that found for FGK dwarfs (e.g. Bonfils *et al.* 2013), at least regarding the short-period domain. This result is expected from the models of planetary formation following the core-accretion paradigm (e.g. Mordasini *et al.* 2012, Ida & Lin 2005).

3. Stellar abundances, planet architecture, and planet composition

The role of stellar properties on the formation of different architectures of planetary systems has also been addressed. Among these, initial suspicions have been raised concerning the metallicity-orbital period relation (e.g. Queloz *et al.* 2000, Sozzetti 2004). Hot-Jupiters have often been identified as orbiting particularly metal-rich stars, even if this trend had not been confirmed from a statistical point of view. Interestingly, recent results do support the existence of a period-metallicity correlation. Beaugé & Nesvorny (2013) have shown that among Kepler small planets there is a lack of short period objects orbiting metal-poor stars. A similar trend has also been found by Adibekyan *et al.* (2013), who have shown that among planets discovered by radial velocity surveys, in all mass domains metal-rich stars have longer period planets than their metal-poor counterparts. It is also interesting to add that preliminary results from an ESO Large Program to search for planets orbiting metal-poor stars (Santos *et al.* 2017) have also failed to detect

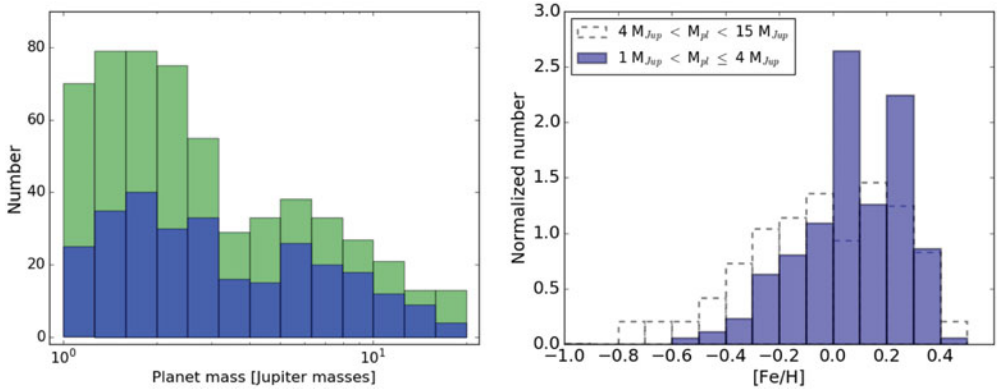

Figure 3. *Left*: Mass distribution of giant planets orbiting solar-type stars. The green histogram includes all hosts, while the blue histogram includes only a selected subsample. A "valley" around $4\,M_{Jup}$ is seen. Right: Metallicity distributions for planets with mass above and below $4\,M_{Jup}$. See Santos *et al.* (2017) for details.

short period planets, even if some intermediate period cases were found (e.g. Mortier *et al.* 2016, Faria *et al.* 2016).

Results from Dawson & Murray-Clay (2013) have also raised the possibility that stellar metallicity may be related to the orbital eccentricity. Analyzing the eccentricity-period diagram for giant planets orbiting solar-type stars they have shown that for intermediate period planets the eccentricity values are higher if the stars are metal-rich. This result, as well as the period-metallicity correlation mentioned above, can likely be explained if higher metallicity stars were able to produce more planets: this would lead to stronger planet-planet scattering, a process that is able to migrate planets into shorter period orbits and lead to the formation of higher eccentricity systems. We note that evidence exists that short period giant planets may result from the outcome of violent migration processes (e.g. Winn *et al.* 2010, Sotiriadis *et al.* 2017). Alternatively, planet-disk interactions could also play a role if the process is metallicity dependent (Tsang *et al.* 2014).

The chemical composition of the stars also seems to be reflected on the structure of the planets that were formed. For instance, the presence of a core (or at least the heavy element content of a giant planet) has been suggested to be related to the metallicity of the star (Guillot *et al.* 2006). Furthermore, even though most studies dealing with the star-planet connection have focused on the global metallicity as a proxy for the metal-content of the star (and likely of the proto-planetary disk), specific chemical abundance ratios may also have an impact on the planets themselves. Different chemical abundances in the disk may result in the formation of planets having different composition and structure (e.g. Carter-Bond *et al.* 2012, Delgado Mena *et al.* 2010, Dorn *et al.* 2015, Thiabaud *et al.* 2015, Santos *et al.* 2015, Dorn *et al.* 2017), a fact that may even change their habitability potential (Noack *et al.* 2014).

Understanding if the chemical abundances we see on the host star are related to the chemical composition we observe on the orbiting planet may provide valuable clues for the modelling of the observations. For instance, it is known that abundance ratios such as Fe/Mg and Fe/Si are very similar on the Sun, Earth, Venus, and Mars – see discussion in Dorn *et al.* (2015). In a recent paper, Dressing *et al.* (2015) has shown that 5 known rocky planets (Kepler-10b, Kepler-36b, Kepler-78b, and Kepler-93b, as well as CoRoT-7b) having precise measurements of the mass and radius seem to follow the same line

https://doi.org/10.1017/S1743921317006421 Published online by Cambridge University Press

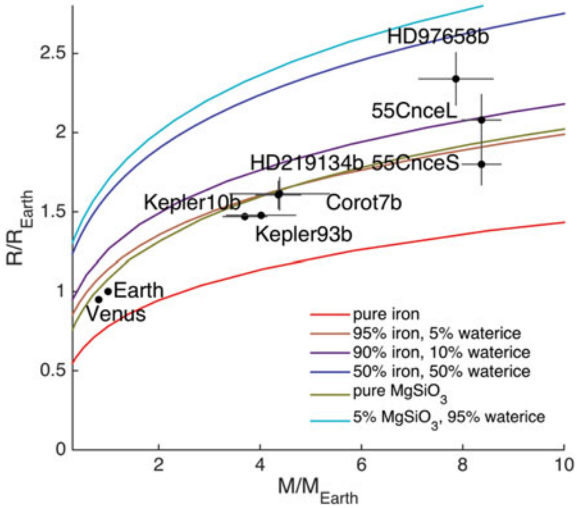

Figure 4. Mass-radius diagram including very low mass (potentially) rocky planets found by different surveys. The lines represent models of planets having different compositions. This plot illustrates how the chemical composition of a planet can be inferred from its position in this plot. From Dorn *et al.* (2017).

in the mass-radius diagram: a line corresponding to the expected position of Earth-like planets (see also Fig. 4). A detailed chemical analysis of 3 of these stars together with a simple stoichiometric model has also shown that the expected planet composition in indeed compatible with Earth-like (Santos *et al.* 2015). If confirmed, these results may be used to constrain the models of planet composition, as long as the abundances of some key elements are known in the stellar atmosphere. Furthermore, this would imply that stars from different galactic populations may even be able to form planets with different composition (Adibekyan *et al.* 2016).

4. Exoplanet research in the Gaia era

The results presented in this paper illustrate how the study of stars with planets and their link with the properties of the planets they host is providing important clues about the processes of planet formation and evolution. Of course, several of the correlations discussed above were only possible thanks to the continuous increase in the number of planets found. As usual, when a new parameter space is explored, unexpected results are obtained. We can thus expect that new star-planet relations will appear in the future as a whole new generation of planet search and characterisation instruments becomes reality. These include ground-based optical spectrographs such as ESPRESSO (ESO-VLT), capable of achieving down to sub m/s precision in RV. A whole new generation of infrared (IR) high resolution spectrographs is also on its way, including instruments such Carmenes@Calar Alto, Spirou@CFHT, and NIRPS (for ESO's 3.6-m). To these we should add the dawn of a new generation of ground- and space-based projects that will search and characterize transiting low mass/radius planets. These include the ESA mission CHEOPS, NASA's TESS (both expected to fly in 2018/2019) and further ahead the ESA PLATO2.0 mission. Finally, a new set of high resolution spectrographs is being planed for a new generation of ELT telescopes.

In this context Gaia will also play a key role. On the one hand, the precise astrometric data gathered is expected to allow the detection of thousands of giant planets orbiting solar-type FGK and M stars, as well as to confirm (and derive precise orbital parameters and masses) for dozens of giant planets discovered by radial-velocity surveys (e.g. Perryman 2014, Sozzetti *et al.* 2014). Given that higher amplitude astrometric signals are expected for higher-mass and longer-period planets, Gaia will focus its planet harvest in this domain, thus probing a mass and period regime that has not yet been fully explored. Finally, the photometry of Gaia will also allow to detect several transiting candidates (Dzigan & Zucker 2012).

But the role of Gaia in the exoplanet field does not limit to planet detections. The exquisite stellar distances will bring new valuable constraints for the derivation of stellar properties (e.g. Stassun *et al.* 2017). These will allow to characterise in detail the properties of planet hosts. Such is fundamental for a precise derivation of planet masses and radii (and thus the planet mean densities): both quantities depend on the measurement of the stellar mass and radius. Furthermore, stellar ages are the only way we can possibly derive the age of the system, an important parameter to understand the planet formation and evolution process. These inputs are all fundamental for the full success of future planet characterisation projects.

I would like to thank the whole exoplanet team at the Instituto de Astrofísica e Ciências do Espaço for the work that led to many of the results presented in this review. This work was supported by Fundação para a Ciência e a Tecnologia (FCT, Portugal) through the research grant through national funds and by FEDER through COMPETE2020 by grants UID/FIS/04434/2013&POCI-01-0145-FEDER-007672 and PTDC-/FIS-AST/1526/2014&POCI-01-0145-FEDER-016886, as well as through Investigador FCT contract nr. IF/00169/2012/CP0150/CT0002.

References

Adibekyan, V. Zh., Delgado Mena, E., Sousa, S. G., *et al.* 2012, *A&A*, 547, A36
Adibekyan, V. Zh., Figueira, P., Santos, N., *et al.* 2013, *A&A*, 560, A51
Adibekyan, V. Zh., Figueira, P., & Santos, N. 2016, *OLEB*, 46, 351
Adibekyan, V. Zh. 2017, *ASP Conference Series*, in press (arXiv:1701.01661)
Andreasen, D. T., Sousa, S. G., & Tsantaki, M. 2017, *A&A*, 600, A69
Beaugé, C. & Nesvorný, D. 2013, *ApJ*, 763, 12
Baumann, P., Ramírez, I., Meléndez, J., Asplund, M., & Lind, K. 2010, *A&A*, 519, 87
Carter-Bond, J. C., O?Brien, D. P., & Raymond, S. N. 2012, *ApJ*, 760, 44
Bonfils, X., Delfosse, X., Udry, S., *et al.* 2013, *A&A*, 549, A109
Burrows, A. S. 2014, *Nature*, 513, 345
Buchhave, Lars A., Latham, David W., Johansen, Anders, *et al.* 2012, *Nature*, 486, 375
Cai, K., Durisen, R. H., & Michael, S., *et al.* 2006, *ApJ*, 636, L149
Dawson, Rebekah I. & Murray-Clay, Ruth A. 2013, *ApJ*, 676, L24
Delgado Mena, E., Israelian, G., González Hernández, J. I., *et al.* 2010, *ApJ*, 725, 2349
Dorn, C., Khan, A., Heng, K., *et al.* 2015, *A&A*, 577, A83
Dorn, C., Hinkel, N. R., & Venturini, J. 2017, *A&A*, 597, A38
Dressing, C. D., Charbonneau, D., Dumusque, X., *et al.* 2015, *ApJ*, 800, 135
Dumusque, X., Lovis, C., Ségransan, D., *et al.* 2011, *A&A*, 535, A55
Dzigan, Y. & Zucker, S. 2012, *ApJ*, 753, L1
Figueira, P., Marmier, M., Bonfils, X., *et al.* 2010, *A&A*, 513, L8
Faria, J. P., Santos, N. C., Figueira, P., *et al.* 2016, *A&A*, 589, A25
Figueira, P., Faria, J. P., Delgado-Mena, E., *et al.* 2014, *A&A*, 570, A21
Fischer, Debra A. & Valenti, Jeff 2005, *ApJ*, 622, 1102
Guillot, T., Santos, N. C., Pont, F., Iro, N., Melo, C., & Ribas, I. 2006, *A&A*, 453, L21

https://doi.org/10.1017/S1743921317006421 Published online by Cambridge University Press

Howard, A. W., Marcy, G. W., Bryson, S. T., *et al.* 2012, *ApJS* 201, 15
Ida, S. & Lin, D. N. C. 2005, *ApJ* 626, 1045
Israelian, Garik, Delgado Mena, Elisa, & Santos, Nuno C. 2009, *Nature*, 462, 189
Johnson, J. A., Aller, K. M., Howard, A. W., & Crepp, J. R. 2010, *PASP* 122, 905
Kaltenegger, L. & Sasselov, D. 2010, *Astrobiology*, 10, 89
Lissauer, Jack J., Dawson, Rebekah I., & Tremaine, Scott 2014, *Nature*, 513, 336
Matsuo, T., Shibai, H., Ootsubo, T., & Tamura, M. 2007, *ApJ*, 662, 1282
Mayor, M. & Queloz, D. 1995, *Nature*, 355, 278
Mayor, M., Lovis, C., & Santos, N. C. 2014, *Nature*, 513, 328
Mordasini, C., Alibert, Y., Benz, W., Klahr, H., & Henning, T. 2012, *A&A*, 541, A97
Mortier, A., Santos, N. C., Sousa, S. G., *et al.* 2013a, *A&A*, 558, A106
Mortier, A., Santos, N. C., Sousa, S. G., *et al.* 2013b, *A&A*, 557, A70
Mortier, A., Faria, J. P., Santos, N. C., *et al.* 2016, *A&A*, 585, A135
Noack, L., Godolt, M., von Paris, P., *et al.* 2014, *P&SS*, 98, 14
Oshagh, M., Santos, N. C., Boisse, I., *et al.* 2013, *A&A*, 556, A19
Perryman, M., Hartman, J., Bakos, Gáspár A., & Lindegren, Lennart 2014, *ApJ*, 797, 14
Queloz, D., Mayor, M., Weber, L., *et al.* 2000, *A&A*, 354, 99
Santos, N. C., Israelian, G., & Mayor, M. 2001, *A&A*, 373, 1019
Santos, N. C., Israelian, G., & Mayor, M. 2004, *A&A*, 415, 1153
Santos, N. C., Sousa, S. G., Mortier, A., *et al.* 2013, *A&A*, 556, A150
Santos, N. C., Adibekyan, V., Mordasini, C., *et al.* 2015, *A&A*, 580, L13
Santos, N. C., Mortier, A., Faria, J. P., *et al.* 2016, *A&A*, 566, A35
Santos, N. C., Adibekyan, V., Figueira, P., *et al.* 2017, *A&A*, 415, 1153
Sotiriadis, Sotiris, Libert, Anne-Sophie, Bitsch, Bertram, Crida, Aurélien 2017, *A&A*, 598, A70
Sousa, S. G., Santos, N. C., Israelian, G., Mayor, M., & Udry, S. 2011, *A&A*, 533, A141
Sozzetti, A. 2004, *MNRAS*, 354, 1194
Sozzetti, A., Giacobbe, P., Lattanzi, M. G., *et al.* 2014, *MNRAS*, 437, 497
Stassun, K. G., Collins, K. A., & Gaudi, B. S. 2017, *AJ*, 153, 136
Torres, Guillermo, Winn, Joshua N. & Holman, Matthew J. 2008, *ApJ*, 677, 1324
Thiabaud, A., Marboeuf, U., Alibert, Y., *et al.* 2014, *A&A*, 562, A27
Tsang, David, Turner, Neal J. & Cumming, Andrew 2014, *ApJ*, 782, 113
Udry, S. & Santos, N. C. 2007, *ARAA*, 45, 397
Valencia, D., O'Connell, R. J., & Sasselov, D. 2006, *Icarus*, 181, 545
Wang, Ji, Fischer, Debra A. 2015, *AJ*, 149, 14
Winn, Joshua N. & Fabrycky, Daniel, Albrecht, Simon, Johnson, John Asher 2010, *ApJ*, 718, L145
Zhu, Wei, Wang, Ji, Huang, Chelsea 2016, *ApJ*, 832, 196