Determination of stellar parameters for M-dwarf stars: the NIR approach

by

Daniel Thaagaard Andreasen

A thesis submitted in conformity with the requirements
for the degree of Doctor of Philosophy
Graduate Department of Departamento de Fisica e Astronomia
University of Porto

Dedication

To Linnea, Henriette, Rico, and Else

For always supporting me

Acknowledgements

When doing a PhD it is important to remember it is more a team effort than the work of an individual. This is something I learned quickly during the last four years. Therefore there are several people I would like to thank.

First and most importantly are my two supervisors, Sérgio and Nuno. They were after me in the beginning of my studies because I was too shy to ask for help; something that I quickly learned I needed to do. They always had their door open for me and all my small questions. It goes without saying that I am thankful for all their guidance during my studies. However, what I am most thankful for is the freedom I have had to explorer paths and ideas on my own, and with them safely on the sideline. This sometimes led to failures and dead ends, but it make me grow as a researcher both by learning from my mistake, but also by prioritising my time.

When I thank Sérgio and Nuno, my official supervisors, I also have to thank Elisa. She has been my third unofficial supervisor almost from the first day. Although she did not have any experience with NIR spectroscopy, she was never afraid of giving her opinion and trying to help. Elisa, your kindness, calmness, and help is priceless! It is extremely reassuring to go on this adventure with three capable supervisors ready to help at any time.

While Sérgio, Nuno, and Elisa are all very capable, they were not alone to answer all my technical questions. Often I went to Vardan to discuss science. Vardan's knowledge is immense, and it has been a pleasure to receive advise and answers when necessary. Similar has the support from Maria in my first two years been valuable. She was my friend here when I arrived, and the one I went to in the beginning with small questions since I was too shy to go with “stupid” questions to my supervisors. Thanks for all the answers you both gave me and the fruitful collaborations.

Luckily my time here in Porto has not only been about work. I have had a lot of good times with new and old friends here. In a random order I would like to thank Elisa, Maria, João, Jorge, Jason, Vardan, Mahmoud, Guilherme, Giancarlo, Andressa, Luisa, Solène, and the entire football team.

A very special thank you to Sofia who made my life easier here in Portugal, and has been a fantastic support and friend. All your time and effort will never be forgotten, and I appreciate all you have done for me.

Now, I know being abroad has been difficult but exciting for me. However, it has mostly been difficult for my family home in Denmark. The last part is specifically dedicated to them: Tusind tak for al jeres tålmodighed, mine kære venner og familie i Danmark. Jeg ved jeg ikke altid har været den bedste til at sende et par beskeder hjem, men alligevel har I altid mødt mig med kram når I har hentet mig i lufthavnen. Det har været en svær tid for mig her, og at tænke på jer derhjemme har virkelig holdt mit mod oppe! Jeg vil i sær gerne takke mine søstre, Henriette og Linnea for altid at have tid til at sludre lidt. Det samme gælder Rico, som også har hentet mig et par gange i lufthavnen. Selvfølgelig bliver jeg nødt til at sige tak til min kære mormor. Din støtte har været uden lige. Der har også altid været mange venner derhjemme som har fundet tid til at bruge et par timer med mig. Tusind tak til i sær Ellen Marie, Maria, Ditte, og Sabrina.

Tusind tak alle sammen/thank you very much everybody!

Abstract

Nam dui ligula, fringilla a, euismod sodales, sollicitudin vel, wisi. Morbi auctor lorem non justo. Nam lacus libero, pretium at, lobortis vitae, ultricies et, tellus. Donec aliquet, tortor sed accumsan bibendum, erat ligula aliquet magna, vitae ornare odio metus a mi. Morbi ac orci et nisl hendrerit mollis. Suspendisse ut massa. Cras nec ante. Pellentesque a nulla. Cum sociis natoque penatibus et magnis dis parturient montes, nascetur ridiculus mus. Aliquam tincidunt urna. Nulla ullamcorper vestibulum turpis. Pellentesque cursus luctus mauris.

Resumo

Nam dui ligula, fringilla a, euismod sodales, sollicitudin vel, wisi. Morbi auctor lorem non justo. Nam lacus libero, pretium at, lobortis vitae, ultricies et, tellus. Donec aliquet, tortor sed accumsan bibendum, erat ligula aliquet magna, vitae ornare odio metus a mi. Morbi ac orci et nisl hendrerit mollis. Suspendisse ut massa. Cras nec ante. Pellentesque a nulla. Cum sociis natoque penatibus et magnis dis parturient montes, nascetur ridiculus mus. Aliquam tincidunt urna. Nulla ullamcorper vestibulum turpis. Pellentesque cursus luctus mauris.

Contents

List of Tables

List of Figures

Chapter 1

Introduction

Ever since the dawn of time, the humankind have looked at the stars and wondered if we are alone in this Universe. To answer this question, one must look toward the field of extrasolar planets (exoplanets). This is a rapidly growing field in astronomy and science in general. Ever since the first confirmed discovery of an exoplanet around a millisecond pulsar in 1992 by Wolszczan and Frail (1992) and three years later, the more interesting exoplanet 51 Peg b discovered around a solar-type star by Mayor and Queloz (1995), more than 3600 exoplanets have been discovered at the time of writing, July 2017[1].

With the discoveries of exoplanets, the main focus is now mainly on finding the twin of Earth, that is a planet that can harbour life as we know it. However, in order to accurately and precisely characterise an exoplanet, it is is crucial to characterise its host star. This is commonly known as "know the star, know the exoplanet". It is possible to obtain planetary global parameters such as its radius and mass if the stellar parameters are accurately known. With high precision it is even possible to distinguish between different planetary bulk compositions such as water-worlds, rocky planets, gaseous planets, iron planets, or exotic combinations of the above.

In this chapter there will be a general introduction to exoplanets, detection methods, and characterisation (Section 1.1). Then a throughout introduction on the exoplanet host stars (Section 1.2), which is the main focus on this thesis. While learning about host stars, and stars in general, the results have wide-spread applications, where some will briefly be discussed in the end of this chapter (Section 1.3) before an introduction on what this thesis will consists of (Section 1.4).

1.1 Exoplanets

The holy grail in the field of exoplanets is to find the first exoplanet with life. This is by no means an easy task. To give an idea of the difficulty of detecting life on an exoplanet, one must understand all the difficulties to simply detect and confirm an exoplanet. This will shortly be described in the sections below where several detection techniques will be introduced.

[1] http://exoplanet.eu/

1.1.1 Detecting exoplanets

There are six main techniques of detecting exoplanets, some with advantages over others. A lot of information about the exoplanets can be extracted when more than one of techniques are used and combined.

It is important to note, that different things might mimic planetary signals, such as stellar activity, the light from a lighter stellar companion (see e.g. Oshagh et al., 2013, 2014). However they will not be described in this thesis. Two techniques are often combined in order to confirm the detection of an exoplanet.

The description of the different detection techniques are inspired by Seager (2010).

1.1.1.1 Transit method

The most successful method, if based on numbers of exoplanets detected, is the transit method. This is a well-known method in astronomy, however only used recently for detecting exoplanets. Before this, it has been used extensively for finding and characterising eclipsing binary stars. The difference here is, that the exoplanet is extremely small and does not radiate (or at least emit very little radiation). An example of an exoplanet transiting a star can be seen in Figure 1.1.

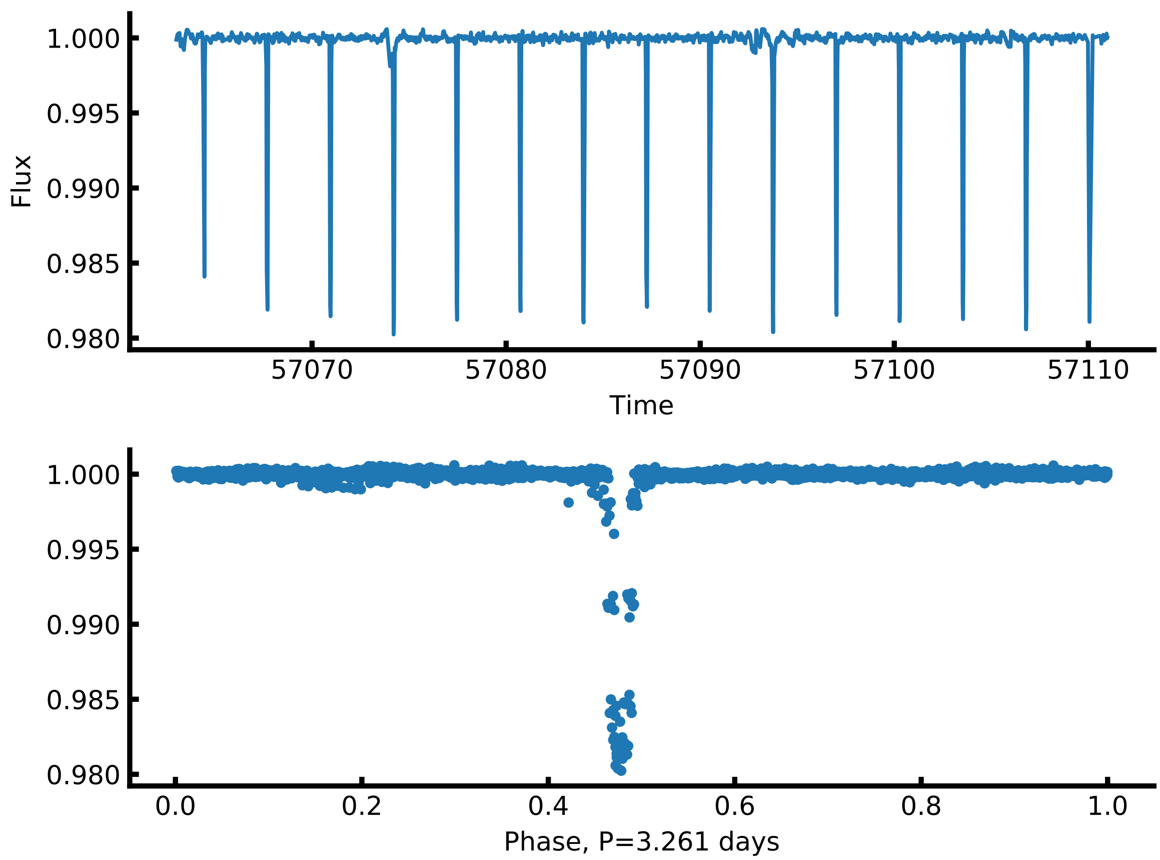

Figure 1.1: *Upper plot*: The lightcurve of a star with an exoplanet transiting. *Lower plot*: The phase curve of the above lightcurve.

As an exoplanet transits its host star, the total brightness from the system will decrease, as the exoplanet blocks some of the light from the star. This dimming in brightness will be seen periodically as the exoplanet orbits its host star. The decrease in brightness as the planet transit the star is directly related to ration between the stellar radius R_* and the planetary radius R_p:

$$k = \sqrt{\frac{R_p}{R_*}}, \tag{1.1}$$

where k is the depth of the transit compared to the total stellar brightness.

It is possible to obtain the radius of an exoplanet with this method. However, detailed analysis of the phase curve of an exoplanet can additionally reveal the surface temperature of the exoplanet. The transit described above is also known as the primary transit. If it is possible to detect the secondary transit, that is when the exoplanet goes behind the star as seen from Earth, the difference in light (planet + star right before secondary transit compared to just star) gives the flux of the planet and thus the surface temperature. This is a difficult task as secondary transits are intrinsic faint.

1.1.1.2 Radial velocity method

The radial velocity method is the indirect study of the motion of the host star using the Doppler effect caused by an orbiting exoplanet. This together with the transit method described above are by far the most successful methods to detect and characterise exoplanets. The periodic signal created by the exoplanet on the host star depends on the mass ratio between the star M_* and the planet M_p:

$$K = \frac{28.4329\,\mathrm{km/s}}{\sqrt{1-e^2}} \frac{M_p \sin i}{M_{\mathrm{Jup}}} \left(\frac{M_* + M_p}{M_\odot}\right)^{-2/3} \left(\frac{P}{1\,\mathrm{year}}\right) \tag{1.2}$$

where K is the semi-amplitude of the sinusoidal, e is the eccentricity, i is the inclination, P is the orbital period, and M_{Jup} is the mass of Jupiter. Since $M_* \gg M_p$, the term $M_* + M_p \simeq M_*$ in order to simplify the equation. Often a circular orbit is assumed, $e = 0$. The sinusoidal motion of the star can be seen in Figure 1.2 where both the time series and the phase curve is presented for an exoplanet.

In order to apply the radial velocity method for detecting exoplanets, it is necessary to collect spectra (high resolution but often not high S/N) in order to cover most part of the phase of the orbit. These spectra are often combined after the detection of the exoplanet, in order to increase the S/N. This combined spectrum can then be used for characterising the host star.

1.1.1.3 Other techniques

The following four techniques have all detected exoplanets, however, they are not widely used and neither has the same level of success as the two methods described above.

Direct imaging Direct imaging is probably the easiest method to understand, however it is quite difficult to actually use this technique. In its core, by carefully blocking the light of a star, it is possible to directly image the exoplanets around it. However, it is extremely difficult to block the light of the host star and find the reflected light of the exoplanet(s) in orbit.

This technique is sensitive to exoplanets which reflect a lot of light, i.e. a high albedo, and in wide orbits as they are less contaminated by the residual starlight.

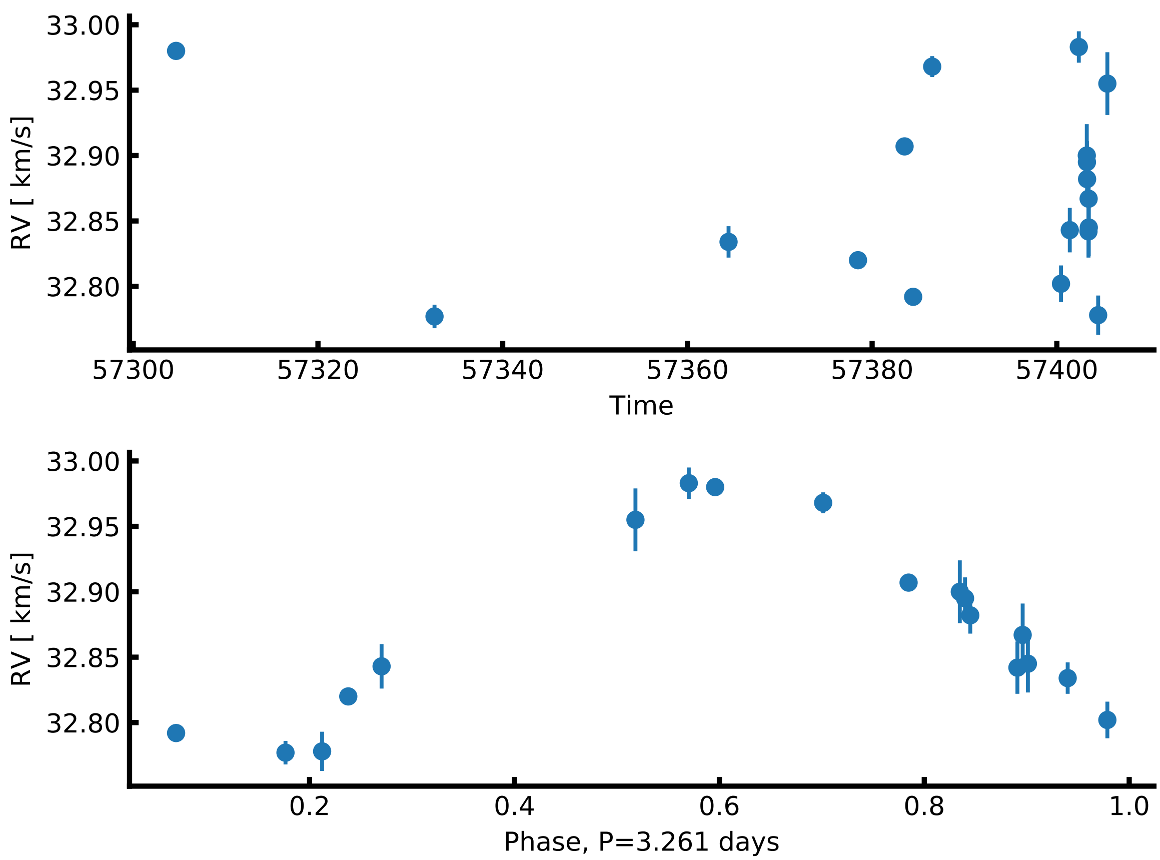

Figure 1.2: *Upper panel*: RV time series of EPIC 9792 from the SOPHIE spectrograph. *Lower panel*: Phase curve of the time series above, using the period of 3.261 days.

Astrometry Using astrometry to detect exoplanets is very similar to the RV method described above in Section 1.1.1.2. Here by carefully detecting the minute motion of a star caused by an exoplanet. Unlike the RV method, this technique (astrometry) actually looks for changes in the coordinates of the star.

This technique is sensitive to massive exoplanets as they cause a larger motion compared to lighter companions.

Transit timing variation This technique of detecting exoplanets is a highly indirect method of detecting exoplanets. Here an a transiting exoplanet has to be detected first as explained in Section 1.1.1.1. Then variations in the occurrence of mid-transit can be detected if a second non-transiting exoplanet interact with the primary transiting exoplanet (planet-planet interaction). This interaction will periodically course the mid-transit to happen ahead/behind of the time if only one exoplanet would be present.

A careful analysis of the transit timing variations (TTV) can give the mass of the secondary non-transiting exoplanet. However, its radius will be unknown. Most of these exoplanets pairs which shows TTV are in an orbital resonant. This technique as well, is more sensitive to massive exoplanets as they will induce a higher signal.

Microlensing This technique is very exotic and not widely used, however since a few exoplanets have been discovered by this technique it deserves a mentioning. The core theory in this technique is the well-known General Relativity by Einstein (1916). Here an observer looks at a distant star (star A) as a star between the observer and the distant star (star B) passes in between the line of sight. Star B will act as a lens and increase the magnitude of star A. This increase of magnitude will reach its maximum as the two stars are most aligned as seen from Earth.

To use this for detecting exoplanet, there will have to be an exoplanet orbiting star B. This act as a microlens, momentarily make a secondary increase in magnitude. The amount of increase in magnitude is related to the mass of the exoplanet. The higher the mass, the higher the effect.

While this exotic technique is interesting and has proven successful, it is not very useful as it only occurs once. The stars observed with this technique are often faint, thus making follow-up RV detection very difficult if not impossible with the current instruments.

1.1.2 Towards the Earth twin

The above mentioned techniques will be used to find the Earth twin. Especially will the two first techniques (transit and RV method) be the ones finding the smallest exoplanets as a wide range of instruments are being developed dedicated for this. Since the detection of the first exoplanet around a solar-type star by Mayor and Queloz (1995), the community has been able to detect lower mass exoplanets as seen in Figure 1.3.

Write about JWST, Espresso, NIRPS, etc.

While the first many discoveries of exoplanets were the, at the time, exotic and strange hot Jupiter-like exoplanets in close orbits, the time have come to detect exoplanets with both lower mass and wider orbits. It is crucial to have high precision instruments and long surveys to detect those exoplanets. Missions as *Kepler* and CoRoT have been excellent for this, since they have focused on few fields of the sky for a long time.

The first place to look for Earth's twin is around a solar twin. However, since these stars are quite hot, the habitable zone will also be far from the host star (Kasting et al., 1993, see e.g.). Indeed, to detect a copy of our own solar system we would need to detect the minute signature of an exoplanet in

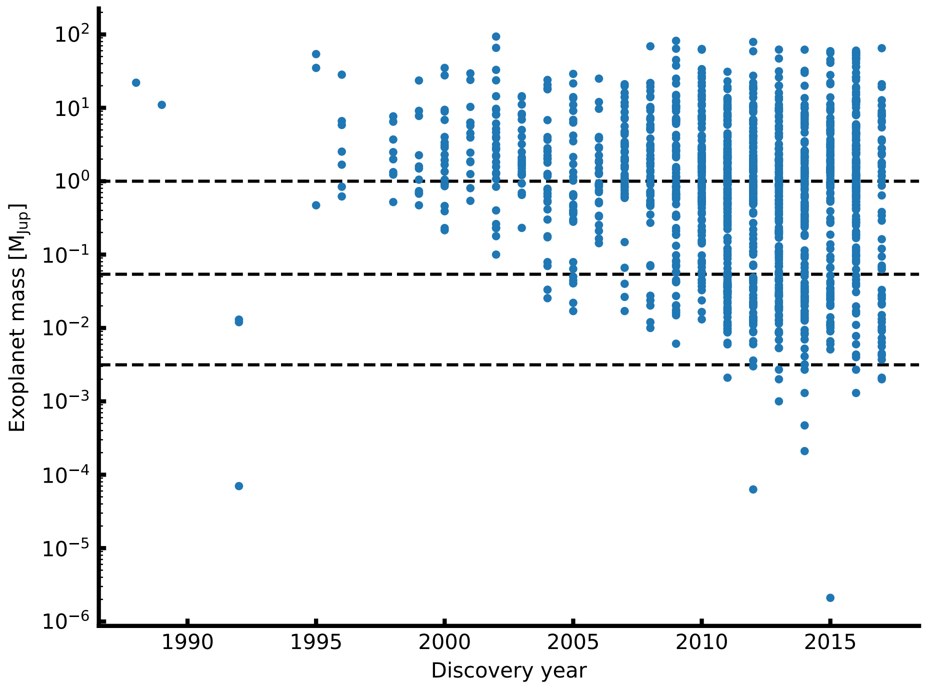

Figure 1.3: The mass of exoplanet since the detection of the first exoplanet until now. The horizontal lines are the mass of Jupiter (upper), Neptune (middle), and Earth (lower).

a 1 year orbit around its host star (a solar twin). If detected with the transit method, more than one transit is needed, hence this will take at least two years, and probably even longer. The endeavour to get the follow-up RV afterwards will also be extremely challenging with today's technology, and only the next generation of instruments will be able to detect these signals.

Therefore, it is not a surprise that an effort has been towards detecting Earth-like planets around less massive stars. These stars (M stars) are also colder, hence the habitable zone will be closer to its host compared to the more massive and hotter stars (Kasting, 1997), and ultimately the period for habitable exoplanets will be shorter. The nature has been kind, since it seems that the M stars are prone to form rocky planets rather than giant gaseous planets (Bonfils et al., 2013; Delfosse et al., 2013). The shorter period means that the surveys can be shorter for these exoplanets. Moreover, since the host stars are smaller the signal from a transit will be easier to detect (see Equation 1.1). Similarly will the RV signal be larger for an Earth-like planet in the habitable zone around an M star compared to a similar exoplanet around a G star. Both due to the lower period and due to the lower mass of the host star (see Equation 1.2).

While M stars seems to be the place to look for the Earth's twin, there are still some challenges to tackle. Foremost is the detailed characterisation of the host star, which are particular troublesome for these stars. This is something that will be focused on in Section 1.2.

1.1.2.1 Detecting life on an exoplanet

After successfully detecting a rocky exoplanet in the habitable zone the next step is to find life. The best hope is to indirectly detect life by finding biosignatures (Kasting and Siefert, 2002) in the exoplanet's atmosphere. Transmission spectroscopy is a technique to study the atmosphere of exoplanets. In this technique a spectrum of the host star and exoplanet is obtained during transit, which is later subtracted of a spectrum of the host star during occultation. Hereby it should be possible to obtain a spectrum of the atmosphere of the exoplanet, which was done by e.g. Charbonneau et al. (2002).

An interesting test to look for biosignatures from the Earthshine on the Moon was performed by Arnold et al. (2002) where they clearly see the blue colour of the Earth's atmosphere due to Rayleigh scattering. They also observed signatures for oxygen, ozone, and water vapours; all important biosignatures in a planetary atmosphere for supporting life.

These signatures, especially oxygen, are from microorganisms through photosynthesis (see e.g. Kasting and Siefert, 2002). However, there might be conditions outside the habitable zone which might sustain life. Here on Earth, extremophiles such as the water bears are known to thrive in extreme places such as boiling water, acid, ice, etc. This might lead to a new window of opportunity in the search of extraterrestrial life (Cavicchioli, 2002).

1.2 Planet host stars

With the present diversity of exoplanets it becomes increasingly important to get an accurate and precise characterisation of the exoplanets in order to study them in samples and on an individual level. An accurate and precise characterisation can give us an idea whether the planet is rocky, composed of water, gaseous, or some other more exotic combination. To characterise stars it is common to use several different methods to gain knowledge about different aspects of a star. If the effective temperature is needed, the reliable determination comes from the analysis of a high resolution and high signal-to-noise (S/N) spectrum. The same is used to identify chemical abundances of the photosphere of the star, while methods like asteroseismology are used to determine the mass and radius of a star, two parameters which are crucial to characterise the orbiting exoplanet.

Some of these methods are described in greater detail in Chapter 3. These methods work best together. In the example given above, the effective temperature is needed before asteroseismology can be used to determine the mass and radius. These two methods goes extremely well together as the most commonly used detection methods (transit and RV) will obtain the data needed. From the transit method, one will obtain a lightcurve which can be used to detect the transits. If these are carefully removed from the lightcurve, the residual might contain stellar oscillations used to perform an asteroseismic analysis. Likewise will the spectra obtained from the RV method to detect/confirm an exoplanet be used for the stellar characterising afterwards by combining them, after shifting to a RV$=0\,$km/s, to increase the S/N. This combined high S/N spectrum is ideal for the spectral analysis of stars.

This tactic where spectroscopic analysis is used in conjunction with asteroseismology have proven very successful (see e.g. Huber et al., 2013) for characterising an exoplanet system (host star and exoplanet). However, it does have its limitations. It can be difficult to detect solar-like oscillations as the stars get colder than the Sun. Especially the community have yet to detect any solar-like oscillations in M dwarf stars(Berdiñas et al., 2017; Rodríguez et al., 2016). Other times the problem is on spectroscopy. Many of the detected exoplanets are from the *Kepler* mission, where many of the host stars are very faint. While it is not impossible to make spectroscopic observations, it is extremely time consuming. Therefore brighter targets are often prioritised, unless there is an exceptional case.

With the search for the Earth twin around the small cool M dwarf stars, it is important to develop reliable methods for the analysis of these cold stars. The tools for detecting the exoplanets are currently more mature than the host star analysis. However, with the advance of NIR spectrographs this is slowly changing. It is general believed that a NIR analysis is needed to characterise M stars. The reason is simple that these stars are so intrinsic faint, that it is important to collect as much flux as possible. This happens in the NIR. Moreover, for spectroscopic studies, the optical spectrum of these stars are severely contaminated by molecular absorption lines, which depress the continuum. It is crucial to get the continuum placement correct during spectroscopic studies. In the NIR the continuum depression is less severe, however still challenging. This can clearly be seen in Figure 1.4 where the optical and NIR part of the spectrum for HD 79210, a K7 dwarf star[2] (Kirkpatrick et al., 1991), is plotted. The spectrum was obtained by CARMENES at the same time and have therefore the same exposure time, hence roughly similar S/N. However, it is clear that the NIR spectrum is far less contaminated by molecular lines.

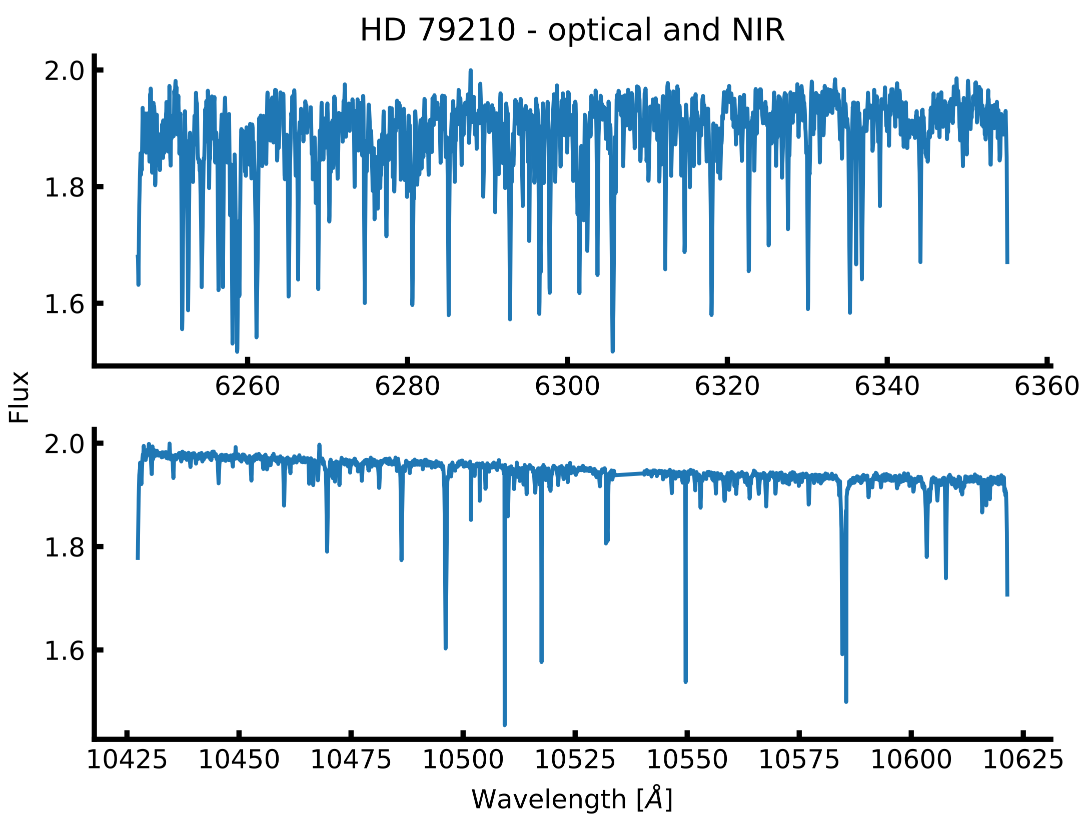

Figure 1.4: Comparison between a optical and NIR part of the spectrum of HD 79210 obtained by the CARMENES spectrograph. This clearly illustrate why NIR spectra are preferred over optical spectra for cool stars. HD 79210 is a K7 dwarf star.

The main goal of this thesis is to work towards a consistent derivation of stellar atmospheric parameters for M stars. Before tackling the M stars, it is important to have a method that work well for solar-like stars (FGK), which are better known during countless studies.

[2] Note that there are very little difference between a K7V and M0V. For the latter case, the situation raised in Figure 1.4 will be more clear.

1.2.1 Star-planet correlations

While the stellar parameters are used to determine the planetary parameters, they can also be sued to reveal correlations between planets and their host stars. This might give insight in the formation and evolution of the planets. This is not a novel idea, and several correlations have been found.

Giant planet and metallicity correlation Since the first discoveries of exoplanets, it became evident that giant planets were systematically orbiting more metal-rich stars compared to stars with no planets. This correlation have been confirmed by several studies (Fischer and Valenti, 2005; Gonzalez, 1997; Mortier et al., 2013b; Santos et al., 2004; Sousa et al., 2008). This correlation in turn establish that core accretion is the main formation mechanism among giant exoplanets (Ida and Lin, 2004; Mordasini et al., 2012; Pollack et al., 1996) and not disc instability (Boss, 2002).

It is important to note that recent studies does not find this correlation for Neptune-like and super-Earth planets (Buchhave et al., 2012; Sousa et al., 2011), thus suggesting these planets belong to a different population.

Abundances of non-iron elements It has been shown that metal-poor stars harbouring gas planets are enhanced in alpha elements[3] (Adibekyan et al., 2012a, see e.g.). This means that other elements also have a role to play in planet formation in metal poor environments. This support the core accretion theory where planetesimals are formed from the condensation of heavy elements.

Lithium and the presence of planets It has been shown by (Delgado Mena et al., 2014; Israelian et al., 2004) that stars hosting planets are significantly more Li depleted compared to stars without planets. This correlation seems to not be affected by different age, mass, or metallicity (Sousa et al., 2010).

1.3 Applications from knowing the stars

While “know the star, know the exoplanet” is the main motivation behind this thesis, it is obviously not the only application behind detailed stellar characterisation. Working towards a better understanding of especially M stars, which consist of to 70% of all the stars in the Milky Way (Bochanski et al., 2010), will also open a new window into the study of different galactic components and galactic chemical evolution. Such a study was done by e.g. Adibekyan et al. (2012b) where spectra of 1111 FGK dwarf stars from the HARPS GTO sample was used to derive chemical abundances of 12 refractory elements. It is possible to separate different galactic populations (thin disk, thick disk, and the halo) by studying the chemical abundances of stars as was shown in Adibekyan et al. (2012b).

In order to do a detailed chemical analysis as described above[4], it is crucial to have reliable and homogeneously derived stellar atmospheric parameters. If the parameters are homogeneously derived, i.e. with the same method, one do not need to worry about removing possible offsets between different methods, and in case of known offsets it is easy to correct for them (this is the case for the method used throughout this thesis, where the surface gravity will be corrected based on another method).

[3] These are elements formed by fusion of a helium core; C, N, O, Ne, Mg, Si, S, Ar, Ca, and Ti.
[4] See also references within Adibekyan et al. (2012b) for other similar studies.

1.4 This thesis

This thesis will be focused on deriving stellar atmospheric parameters for FGK stars, making the bridge towards M stars. The theory of stellar atmospheres in a nutshell is described in Chapter 2, setting up all the tools to derived them as described in Chapter 3. In this chapter the description of other useful and common methods for deriving similar and different parameters are also presented. Thereafter the knowledge will all be used in Chapter 4. First by obtaining a NIR line list containing Fe I and Fe II lines, then by the derivation of parameters for HD 20010 (F sub-giant). Before deriving parameters for two K giants, the NIR line list will be revisited.

After focusing on the NIR spectra, the optical counterpart of the method described below will be used to derive parameters for 50 planet-host stars for an online catalogue of homogeneously derived parameters (SWEET-Cat) in Chapter 5.

Last in Chapter 6 the future of the work established here will be discussed along with the results already obtained. This will round of the thesis.

After the last chapter there will be an appendix with large tables that would otherwise distract the reader from the main points. This appendix is followed by the bibliography for this thesis.

Bibliography

Adamów, M., Niedzielski, A., Villaver, E., Wolszczan, A., and Nowak, G.: 2014, *A&A* **5**69, A55

Adibekyan, V., Delgado-Mena, E., Figueira, P., Sousa, S. G., Santos, N. C., González Hernández, J. I., Minchev, I., Faria, J. P., Israelian, G., Harutyunyan, G., Suárez-Andrés, L., and Hakobyan, A. A.: 2016, *A&A* **5**92, A87

Adibekyan, V. Z., Benamati, L., Santos, N. C., Alves, S., Lovis, C., Udry, S., Israelian, G., Sousa, S. G., Tsantaki, M., Mortier, A., Sozzetti, A., and De Medeiros, J. R.: 2015, *MNRAS* **4**50, 1900

Adibekyan, V. Z., Figueira, P., Santos, N. C., Mortier, A., Mordasini, C., Delgado Mena, E., Sousa, S. G., Correia, A. C. M., Israelian, G., and Oshagh, M.: 2013, *A&A* **5**60, A51

Adibekyan, V. Z., Santos, N. C., Sousa, S. G., Israelian, G., Delgado Mena, E., González Hernández, J. I., Mayor, M., Lovis, C., and Udry, S.: 2012a, *A&A* **5**43, A89

Adibekyan, V. Z., Sousa, S. G., Santos, N. C., Delgado Mena, E., González Hernández, J. I., Israelian, G., Mayor, M., and Khachatryan, G.: 2012b, *A&A* **5**45, A32

Aerts, C., Christensen-Dalsgaard, J., and Kurtz, D. W.: 2010, *Asteroseismology*, Springer-Verlag

Anderson, D. R., Collier Cameron, A., Gillon, M., Hellier, C., Jehin, E., Lendl, M., Maxted, P. F. L., Queloz, D., Smalley, B., Smith, A. M. S., Triaud, A. H. M. J., West, R. G., Pepe, F., Pollacco, D., Ségransan, D., Todd, I., and Udry, S.: 2012, *MNRAS* **4**22, 1988

Andreasen, D. T., Sousa, S. G., Delgado Mena, E., Santos, N. C., Lebzelter, T., Mucciarelli, A., and Neil, J. J.: 2017a, *A&A* **5**85, A143

Andreasen, D. T., Sousa, S. G., Delgado Mena, E., Santos, N. C., Tsantaki, M., Rojas-Ayala, B., and Neves, V.: 2016, *A&A* **5**85, A143

Andreasen, D. T., Sousa, S. G., Tsantaki, M., Teixeira, G. D. C., Mortier, A., Santos, N. C., Suárez-Andrés, L., Delgado Mena, E., and Ferreira, A. C. S.: 2017b, *A&A* **6**00, A69

Arnold, L., Gillet, S., Lardière, O., Riaud, P., and Schneider, J.: 2002, *A&A* **3**92, 231

Balachandran, S.: 1990, *ApJ* **3**54, 310

Barclay, T., Rowe, J. F., Lissauer, J. J., Huber, D., Fressin, F., Howell, S. B., Bryson, S. T., Chaplin, W. J., Désert, J.-M., Lopez, E. D., Marcy, G. W., Mullally, F., Ragozzine, D., Torres, G., Adams, E. R., Agol, E., Barrado, D., Basu, S., Bedding, T. R., Buchhave, L. A., Charbonneau, D., Christiansen, J. L., Christensen-Dalsgaard, J., Ciardi, D., Cochran, W. D., Dupree, A. K., Elsworth, Y., Everett, M., Fischer, D. A., Ford, E. B., Fortney, J. J., Geary, J. C., Haas, M. R., Handberg, R., Hekker, S., Henze, C. E., Horch, E., Howard, A. W., Hunter, R. C., Isaacson, H., Jenkins, J. M., Karoff, C., Kawaler, S. D., Kjeldsen, H., Klaus, T. C., Latham, D. W., Li, J., Lillo-Box, J., Lund, M. N., Lundkvist, M., Metcalfe, T. S., Miglio, A., Morris, R. L., Quintana, E. V., Stello, D., Smith, J. C., Still, M., and Thompson, S. E.: 2013, *Nature* **4**94, 452

Bedding, T. R., Mosser, B., Huber, D., Montalbán, J., Beck, P., Christensen-Dalsgaard, J., Elsworth, Y. P., García, R. A., Miglio, A., Stello, D., White, T. R., De Ridder, J., Hekker, S., Aerts, C., Barban, C., Belkacem, K., Broomhall, A.-M., Brown, T. M., Buzasi, D. L., Carrier, F., Chaplin, W. J., di Mauro, M. P., Dupret, M.-A., Frandsen, S., Gilliland, R. L., Goupil, M.-J., Jenkins, J. M., Kallinger, T., Kawaler, S., Kjeldsen, H., Mathur, S., Noels, A., Silva Aguirre, V., and Ventura, P.: 2011, *Nature* **4**71, 608

Bedell, M., Meléndez, J., Bean, J. L., Ramírez, I., Asplund, M., Alves-Brito, A., Casagrande, L., Dreizler, S., Monroe, T., Spina, L., and Tucci Maia, M.: 2015, *A&A* **5**81, A34

Berdiñas, Z. M., Rodríguez-López, C., Amado, P. J., Anglada-Escudé, G., Barnes, J. R., MacDonald, J., Zechmeister, M., and Sarmiento, L. F.: 2017, *MNRAS* **4**69, 4268

Bertaux, J. L., Lallement, R., Ferron, S., Boonne, C., and Bodichon, R.: 2014, *A&A* **5**64, A46

Blackwell, D. E. and Shallis, M. J.: 1977, *MNRAS* **1**80, 177

Bochanski, J. J., Hawley, S. L., Covey, K. R., West, A. A., Reid, I. N., Golimowski, D. A., and Ivezić, Ž.: 2010, *AJ* **1**39, 2679

Boisse, I., Hartman, J. D., Bakos, G. Á., Penev, K., Csubry, Z., Béky, B., Latham, D. W., Bieryla, A., Torres, G., Kovács, G., Buchhave, L. A., Hansen, T., Everett, M., Esquerdo, G. A., Szklenár, T., Falco, E., Shporer, A., Fulton, B. J., Noyes, R. W., Stefanik, R. P., Lázár, J., Papp, I., and Sári, P.: 2013, *A&A* **5**58, A86

Bonfils, X., Delfosse, X., Udry, S., Forveille, T., Mayor, M., Perrier, C., Bouchy, F., Gillon, M., Lovis, C., Pepe, F., Queloz, D., Santos, N. C., Ségransan, D., and Bertaux, J.-L.: 2013, *A&A* **5**49, A109

Boss, A. P.: 2002, *ApJL* **5**67, L149

Brucalassi, A., Pasquini, L., Saglia, R., Ruiz, M. T., Bonifacio, P., Bedin, L. R., Biazzo, K., Melo, C., Lovis, C., and Randich, S.: 2014, *A&A* **5**61, L9

Bryan, M. L., Alsubai, K. A., Latham, D. W., Parley, N. R., Collier Cameron, A., Quinn, S. N., Carter, J. A., Fulton, B. J., Berlind, P., Brown, W. R., Buchhave, L. A., Calkins, M. L., Esquerdo, G. A., Fűrész, G., Gråe Jørgensen, U., Horne, K. D., Stefanik, R. P., Street, R. A., Torres, G., West, R. G., Dominik, M., Harpsøe, K. B. W., Liebig, C., Calchi Novati, S., Ricci, D., and Skottfelt, J. F.: 2012, *ApJ* **7**50, 84

Buchhave, L. A., Latham, D. W., Johansen, A., Bizzarro, M., Torres, G., Rowe, J. F., Batalha, N. M., Borucki, W. J., Brugamyer, E., Caldwell, C., Bryson, S. T., Ciardi, D. R., Cochran, W. D., Endl, M., Esquerdo, G. A., Ford, E. B., Geary, J. C., Gilliland, R. L., Hansen, T., Isaacson, H., Laird, J. B., Lucas, P. W., Marcy, G. W., Morse, J. A., Robertson, P., Shporer, A., Stefanik, R. P., Still, M., and Quinn, S. N.: 2012, *Nature* **4**86, 375

Campante, T. L., Barclay, T., Swift, J. J., Huber, D., Adibekyan, V. Z., Cochran, W., Burke, C. J., Isaacson, H., Quintana, E. V., Davies, G. R., Silva Aguirre, V., Ragozzine, D., Riddle, R., Baranec, C., Basu, S., Chaplin, W. J., Christensen-Dalsgaard, J., Metcalfe, T. S., Bedding, T. R., Handberg, R., Stello, D., Brewer, J. M., Hekker, S., Karoff, C., Kolbl, R., Law, N. M., Lundkvist, M., Miglio, A., Rowe, J. F., Santos, N. C., Van Laerhoven, C., Arentoft, T., Elsworth, Y. P., Fischer, D. A., Kawaler, S. D., Kjeldsen, H., Lund, M. N., Marcy, G. W., Sousa, S. G., Sozzetti, A., and White, T. R.: 2015, *ApJ* **7**99, 170

Casagrande, L., Portinari, L., and Flynn, C.: 2006, *MNRAS* **3**73, 13

Cavicchioli, R.: 2002, *Astrobiology* **2**, 281

Cayrel, R.: 1988, in G. Cayrel de Strobel and M. Spite (eds.), *The Impact of Very High S/N Spectroscopy on Stellar Physics*, Vol. 132 of *IAU Symposium*, p. 345

Chaplin, W. J., Kjeldsen, H., Christensen-Dalsgaard, J., Basu, S., Miglio, A., Appourchaux, T., Bedding, T. R., Elsworth, Y., García, R. A., Gilliland, R. L., Girardi, L., Houdek, G., Karoff, C., Kawaler, S. D., Metcalfe, T. S., Molenda-Żakowicz, J., Monteiro, M. J. P. F. G., Thompson, M. J., Verner, G. A., Ballot, J., Bonanno, A., Brandão, I. M., Broomhall, A.-M., Bruntt, H., Campante, T. L., Corsaro, E., Creevey, O. L., Doğan, G., Esch, L., Gai, N., Gaulme, P., Hale, S. J., Handberg, R., Hekker, S., Huber, D., Jiménez, A., Mathur, S., Mazumdar, A., Mosser, B., New, R., Pinsonneault, M. H., Pricopi, D., Quirion, P.-O., Régulo, C., Salabert, D., Serenelli, A. M., Silva Aguirre, V., Sousa, S. G., Stello, D., Stevens, I. R., Suran, M. D., Uytterhoeven, K., White, T. R., Borucki, W. J., Brown, T. M., Jenkins, J. M., Kinemuchi, K., Van Cleve, J., and Klaus, T. C.: 2011, *Science* **3**32, 213

Charbonneau, D., Brown, T. M., Noyes, R. W., and Gilliland, R. L.: 2002, *ApJ* **5**68, 377

Christensen-Dalsgaard, J., Kjeldsen, H., Brown, T. M., Gilliland, R. L., Arentoft, T., Frandsen, S., Quirion, P.-O., Borucki, W. J., Koch, D., and Jenkins, J. M.: 2010, *ApJL* **7**13, L164

Collins, K. A., Eastman, J. D., Beatty, T. G., Siverd, R. J., Gaudi, B. S., Pepper, J., Kielkopf, J. F., Johnson, J. A., Howard, A. W., Fischer, D. A., Manner, M., Bieryla, A., Latham, D. W., Fulton, B. J., Gregorio, J., Buchhave, L. A., Jensen, E. L. N., Stassun, K. G., Penev, K., Crepp, J. R., Hinkley, S., Street, R. A., Cargile, P., Mack, C. E., Oberst, T. E., Avril, R. L., Mellon, S. N., McLeod, K. K., Penny, M. T., Stefanik, R. P., Berlind, P., Calkins, M. L., Mao, Q., Richert, A. J. W., DePoy, D. L., Esquerdo, G. A., Gould, A., Marshall, J. L., Oelkers, R. J., Pogge, R. W., Trueblood, M., and Trueblood, P.: 2014, *AJ* **1**47, 39

Czekala, I., Andrews, S. M., Mandel, K. S., Hogg, D. W., and Green, G. M.: 2015, *ApJ* **8**12, 128

Dekker, H., D'Odorico, S., Kaufer, A., Delabre, B., and Kotzlowski, H.: 2000, in M. Iye and A. F. Moorwood (eds.), *Optical and IR Telescope Instrumentation and Detectors*, Vol. 4008 of *Proceedings of the SPIE*, pp 534–545

Delfosse, X., Bonfils, X., Forveille, T., Udry, S., Mayor, M., Bouchy, F., Gillon, M., Lovis, C., Neves, V., Pepe, F., Perrier, C., Queloz, D., Santos, N. C., and Ségransan, D.: 2013, *A&A* **5**53, A8

Delgado Mena, E., Israelian, G., González Hernández, J. I., Sousa, S. G., Mortier, A., Santos, N. C., Adibekyan, V. Z., Fernandes, J., Rebolo, R., Udry, S., and Mayor, M.: 2014, *A&A* **5**62, A92

Delrez, L., Van Grootel, V., Anderson, D. R., Collier-Cameron, A., Doyle, A. P., Fumel, A., Gillon, M., Hellier, C., Jehin, E., Lendl, M., Neveu-VanMalle, M., Maxted, P. F. L., Pepe, F., Pollacco, D., Queloz, D., Ségransan, D., Smalley, B., Smith, A. M. S., Southworth, J., Triaud, A. H. M. J., Udry, S., and West, R. G.: 2014, *A&A* **5**63, A143

Donati, J.-F.: 2003, in J. Trujillo-Bueno and J. Sanchez Almeida (eds.), *Solar Polarization*, Vol. 307 of *Astronomical Society of the Pacific Conference Series*, p. 41

Ducati, J. R.: 2002, *VizieR Online Data Catalog* 2237

Einstein, A.: 1916, *Annalen der Physik* **3**54, 769

Favata, F., Micela, G., and Sciortino, S.: 1997, *A&A* **3**23, 809

Figueira, P., Oshagh, M., Adibekyan, V. Z., and Santos, N. C.: 2014, *A&A* **5**72, A51

Fischer, D. A. and Valenti, J.: 2005, *ApJ* **6**22, 1102

Frandsen, S. and Lindberg, B.: 1999, in H. Karttunen and V. Piirola (eds.), *Astrophysics with the NOT*, p. 71

Gillon, M., Anderson, D. R., Collier-Cameron, A., Doyle, A. P., Fumel, A., Hellier, C., Jehin, E., Lendl, M., Maxted, P. F. L., Montalbán, J., Pepe, F., Pollacco, D., Queloz, D., Ségransan, D., Smith, A. M. S., Smalley, B., Southworth, J., Triaud, A. H. M. J., Udry, S., and West, R. G.: 2013, *A&A* **5**52, A82

Gómez Maqueo Chew, Y., Faedi, F., Pollacco, D., Brown, D. J. A., Doyle, A. P., Collier Cameron, A., Gillon, M., Lendl, M., Smalley, B., Triaud, A. H. M. J., West, R. G., Wheatley, P. J., Busuttil, R., Liebig, C., Anderson, D. R., Armstrong, D. J., Barros, S. C. C., Bento, J., Bochinski, J., Burwitz, V., Delrez, L., Enoch, B., Fumel, A., Haswell, C. A., Hébrard, G., Hellier, C., Holmes, S., Jehin, E., Kolb, U., Maxted, P. F. L., McCormac, J., Miller, G. R. M., Norton, A. J., Pepe, F., Queloz, D., Rodríguez, J., Ségransan, D., Skillen, I., Stassun, K. G., Udry, S., and Watson, C.: 2013, *A&A* **5**59, A36

Gonzalez, G.: 1997, *MNRAS* **2**85, 403

Gonzalez, G., Carlson, M. K., and Tobin, R. W.: 2010, *MNRAS* **4**03, 1368

Gonzalez, G. and Laws, C.: 2000, *AJ* **1**19, 390

Gray, D. F.: 2005, *The Observation and Analysis of Stellar Photospheres, 3rd ed.*

Griffin, R. and Griffin, R.: 1967, *MNRAS* **1**37, 253

Grundahl, F., Fredslund Andersen, M., Christensen-Dalsgaard, J., Antoci, V., Kjeldsen, H., Handberg, R., Houdek, G., Bedding, T. R., Pallé, P. L., Jessen-Hansen, J., Silva Aguirre, V., White, T. R., Frandsen, S., Albrecht, S., Andersen, M. I., Arentoft, T., Brogaard, K., Chaplin, W. J., Harpsøe, K., Jørgensen, U. G., Karovicova, I., Karoff, C., Kjærgaard Rasmussen, P., Lund, M. N., Sloth Lundkvist, M., Skottfelt, J., Norup Sørensen, A., Tronsgaard, R., and Weiss, E.: 2017, *ApJ* **8**36, 142

Gustafsson, B., Edvardsson, B., Eriksson, K., Jørgensen, U. G., Nordlund, Å., and Plez, B.: 2008, *A&A* **4**86, 951

Hartman, J. D.: 2010, *ApJL* **7**17, L138

Hartman, J. D., Bakos, G. Á., Béky, B., Torres, G., Latham, D. W., Csubry, Z., Penev, K., Shporer, A., Fulton, B. J., Buchhave, L. A., Johnson, J. A., Howard, A. W., Marcy, G. W., Fischer, D. A., Kovács, G., Noyes, R. W., Esquerdo, G. A., Everett, M., Szklenár, T., Quinn, S. N., Bieryla, A., Knox, R. P., Hinz, P., Sasselov, D. D., Fűrész, G., Stefanik, R. P., Lázár, J., Papp, I., and Sári, P.: 2012, *AJ* **1**44, 139

Hartman, J. D., Bakos, G. Á., Torres, G., Kovács, G., Johnson, J. A., Howard, A. W., Marcy, G. W., Latham, D. W., Bieryla, A., Buchhave, L. A., Bhatti, W., Béky, B., Csubry, Z., Penev, K., de Val-Borro, M., Noyes, R. W., Fischer, D. A., Esquerdo, G. A., Everett, M., Szklenár, T., Zhou, G., Bayliss, D., Shporer, A., Fulton, B. J., Sanchis-Ojeda, R., Falco, E., Lázár, J., Papp, I., and Sári, P.: 2014a, *AJ* **1**47, 128

Hartman, J. D., Bakos, G. Á., Torres, G., Kovács, G., Johnson, J. A., Howard, A. W., Marcy, G. W., Latham, D. W., Bieryla, A., Buchhave, L. A., Bhatti, W., Béky, B., Csubry, Z., Penev, K., de Val-Borro, M., Noyes, R. W., Fischer, D. A., Esquerdo, G. A., Everett, M., Szklenár, T., Zhou, G., Bayliss, D., Shporer, A., Fulton, B. J., Sanchis-Ojeda, R., Falco, E., Lázár, J., Papp, I., and Sári, P.: 2014b, *AJ* **1**47, 128

Hébrard, G., Arnold, L., Forveille, T., Correia, A. C. M., Laskar, J., Bonfils, X., Boisse, I., Díaz, R. F., Hagelberg, J., Sahlmann, J., Santos, N. C., Astudillo-Defru, N., Borgniet, S., Bouchy, F., Bourrier, V., Courcol, B., Delfosse, X., Deleuil, M., Demangeon, O., Ehrenreich, D., Gregorio, J., Jovanovic, N., Labrevoir, O., Lagrange, A.-M., Lovis, C., Lozi, J., Moutou, C., Montagnier, G., Pepe, F., Rey, J., Santerne, A., Ségransan, D., Udry, S., Vanhuysse, M., Vigan, A., and Wilson, P. A.: 2016, *A&A* **5**88, A145

Hébrard, G., Collier Cameron, A., Brown, D. J. A., Díaz, R. F., Faedi, F., Smalley, B., Anderson, D. R., Armstrong, D., Barros, S. C. C., Bento, J., Bouchy, F., Doyle, A. P., Enoch, B., Gómez Maqueo Chew, Y., Hébrard, É. M., Hellier, C., Lendl, M., Lister, T. A., Maxted, P. F. L., McCormac, J., Moutou, C., Pollacco, D., Queloz, D., Santerne, A., Skillen, I., Southworth, J., Tregloan-Reed, J., Triaud, A. H. M. J., Udry, S., Vanhuysse, M., Watson, C. A., West, R. G., and Wheatley, P. J.: 2013, *A&A* **5**49, A134

Hellier, C., Anderson, D. R., Cameron, A. C., Delrez, L., Gillon, M., Jehin, E., Lendl, M., Maxted, P. F. L., Pepe, F., Pollacco, D., Queloz, D., Ségransan, D., Smalley, B., Smith, A. M. S., Southworth, J., Triaud, A. H. M. J., Udry, S., and West, R. G.: 2014, *MNRAS* **4**40, 1982

Hellier, C., Anderson, D. R., Collier Cameron, A., Doyle, A. P., Fumel, A., Gillon, M., Jehin, E., Lendl, M., Maxted, P. F. L., Pepe, F., Pollacco, D., Queloz, D., Ségransan, D., Smalley, B., Smith, A. M. S., Southworth, J., Triaud, A. H. M. J., Udry, S., and West, R. G.: 2012, *MNRAS* **4**26, 739

Hinkel, N. R., Young, P. A., Pagano, M. D., Desch, S. J., Anbar, A. D., Adibekyan, V., Blanco-Cuaresma, S., Carlberg, J. K., Delgado Mena, E., Liu, F., Nordlander, T., Sousa, S. G., Korn, A., Gruyters, P., Heiter, U., Jofré, P., Santos, N. C., and Soubiran, C.: 2016, *ApJS* **2**26, 4

Hinkle, K., Wallace, L., and Livingston, W.: 1995a, *Publications of the ASP* **1**07, 1042

Hinkle, K. H., Wallace, L., and Livingston, W.: 1995b, in A. J. Sauval, R. Blomme, and N. Grevesse (eds.), *Laboratory and Astronomical High Resolution Spectra*, Vol. 81 of *Astronomical Society of the Pacific Conference Series*, p. 66

Howard, A. W., Johnson, J. A., Marcy, G. W., Fischer, D. A., Wright, J. T., Henry, G. W., Isaacson, H., Valenti, J. A., Anderson, J., and Piskunov, N. E.: 2011, *ApJ* **7**30, 10

Huber, D., Chaplin, W. J., Christensen-Dalsgaard, J., Gilliland, R. L., Kjeldsen, H., Buchhave, L. A., Fischer, D. A., Lissauer, J. J., Rowe, J. F., Sanchis-Ojeda, R., Basu, S., Handberg, R., Hekker, S., Howard, A. W., Isaacson, H., Karoff, C., Latham, D. W., Lund, M. N., Lundkvist, M., Marcy, G. W., Miglio, A., Silva Aguirre, V., Stello, D., Arentoft, T., Barclay, T., Bedding, T. R., Burke, C. J., Christiansen, J. L., Elsworth, Y. P., Haas, M. R., Kawaler, S. D., Metcalfe, T. S., Mullally, F., and Thompson, S. E.: 2013, *ApJ* **7**67, 127

Huber, D., Silva Aguirre, V., Matthews, J. M., Pinsonneault, M. H., Gaidos, E., García, R. A., Hekker, S., Mathur, S., Mosser, B., Torres, G., Bastien, F. A., Basu, S., Bedding, T. R., Chaplin, W. J., Demory, B.-O., Fleming, S. W., Guo, Z., Mann, A. W., Rowe, J. F., Serenelli, A. M., Smith, M. A., and Stello, D.: 2014, *ApJS* **2**11, 2

Husser, T.-O., Wende-von Berg, S., Dreizler, S., Homeier, D., Reiners, A., Barman, T., and Hauschildt, P. H.: 2013, *A&A* **5**53, A6

Ida, S. and Lin, D. N. C.: 2004, *ApJ* **6**16, 567

Israelian, G., Santos, N. C., Mayor, M., and Rebolo, R.: 2004, *A&A* **4**14, 601

Jofré, P., Heiter, U., Soubiran, C., Blanco-Cuaresma, S., Worley, C. C., Pancino, E., Cantat-Gaudin, T., Magrini, L., Bergemann, M., González Hernández, J. I., Hill, V., Lardo, C., de Laverny, P., Lind, K., Masseron, T., Montes, D., Mucciarelli, A., Nordlander, T., Recio Blanco, A., Sobeck, J., Sordo, R., Sousa, S. G., Tabernero, H., Vallenari, A., and Van Eck, S.: 2014, *A&A* **5**64, A133

Johnson, J. A., Clanton, C., Howard, A. W., Bowler, B. P., Henry, G. W., Marcy, G. W., Crepp, J. R., Endl, M., Cochran, W. D., MacQueen, P. J., Wright, J. T., and Isaacson, H.: 2011, *ApJS* **1**97, 26

Jones, M. I., Jenkins, J. S., Rojo, P., and Melo, C. H. F.: 2011, *A&A* **5**36, A71

Jones, M. I., Jenkins, J. S., Rojo, P., Olivares, F., and Melo, C. H. F.: 2015, *A&A* **5**80, A14

Kasting, J. F.: 1997, *Origins of Life and Evolution of the Biosphere* **2**7, 291

Kasting, J. F. and Siefert, J. L.: 2002, *Science* **2**96, 1066

Kasting, J. F., Whitmire, D. P., and Reynolds, R. T.: 1993, *Icarus* **1**01, 108

Kaufer, A., Stahl, O., Tubbesing, S., Nørregaard, P., Avila, G., Francois, P., Pasquini, L., and Pizzella, A.: 1999, *The Messenger* **9**5, 8

Kippenhahn, R. and Weigert, A.: 1994, *Stellar Structure and Evolution*, Springer-Verlag

Kipping, D. M., Bakos, G. Á., Hartman, J., Torres, G., Shporer, A., Latham, D. W., Kovács, G., Noyes, R. W., Howard, A. W., Fischer, D. A., Johnson, J. A., Marcy, G. W., Béky, B., Perumpilly, G., Esquerdo, G. A., Sasselov, D. D., Stefanik, R. P., Lázár, J., Papp, I., and Sári, P.: 2010, *ApJ* **7**25, 2017

Kirkpatrick, J. D., Henry, T. J., and McCarthy, Jr., D. W.: 1991, *ApJS* **7**7, 417

Kjeldsen, H. and Bedding, T. R.: 1995, *A&A* **2**93, 87

Kopparapu, R. K., Ramirez, R., Kasting, J. F., Eymet, V., Robinson, T. D., Mahadevan, S., Terrien, R. C., Domagal-Goldman, S., Meadows, V., and Deshpande, R.: 2013, *ApJ* **7**65, 131

Kunitomo, M., Ikoma, M., Sato, B., Katsuta, Y., and Ida, S.: 2011, *ApJ* **7**37, 66

Kupka, F. G., Ryabchikova, T. A., Piskunov, N. E., Stempels, H. C., and Weiss, W. W.: 2000, *Baltic Astronomy* **9**, 590

Kurucz, R.: 1993, *ATLAS9 Stellar Atmosphere Programs and 2 km/s grid. Kurucz CD-ROM No. 13. Cambridge, Mass.: Smithsonian Astrophysical Observatory, 1993.* 13

Lebzelter, T., Seifahrt, A., Uttenthaler, S., Ramsay, S., Hartman, H., Nieva, M.-F., Przybilla, N., Smette, A., Wahlgren, G. M., Wolff, B., Hussain, G. A. J., Käufl, H. U., and Seemann, U.: 2012, *A&A* **5**39, A109

Lee, B.-C., Han, I., and Park, M.-G.: 2013, *A&A* **5**49, A2

Lee, B.-C., Han, I., Park, M.-G., Mkrtichian, D. E., Hatzes, A. P., and Kim, K.-M.: 2014, *A&A* **5**66, A67

Lindgren, S., Heiter, U., and Seifahrt, A.: 2016, *A&A* **5**86, A100

Mayor, M., Pepe, F., Queloz, D., Bouchy, F., Rupprecht, G., Lo Curto, G., Avila, G., Benz, W., Bertaux, J.-L., Bonfils, X., Dall, T., Dekker, H., Delabre, B., Eckert, W., Fleury, M., Gilliotte, A., Gojak, D., Guzman, J. C., Kohler, D., Lizon, J.-L., Longinotti, A., Lovis, C., Megevand, D., Pasquini, L., Reyes, J., Sivan, J.-P., Sosnowska, D., Soto, R., Udry, S., van Kesteren, A., Weber, L., and Weilenmann, U.: 2003, *The Messenger* **1**14, 20

Mayor, M. and Queloz, D.: 1995, *A Jupiter-mass companion to a solar-type star*

McWilliam, A.: 1990, *ApJS* **7**4, 1075

Mordasini, C., Alibert, Y., Benz, W., Klahr, H., and Henning, T.: 2012, *A&A* **5**41, A97

Mortier, A., Santos, N. C., Sousa, S., Israelian, G., Mayor, M., and Udry, S.: 2013a, *A&A* **5**51, A112

Mortier, A., Santos, N. C., Sousa, S. G., Adibekyan, V. Z., Delgado Mena, E., Tsantaki, M., Israelian, G., and Mayor, M.: 2013b, *A&A* **5**57, A70

Mortier, A., Sousa, S. G., Adibekyan, V. Z., Brandão, I. M., and Santos, N. C.: 2014, *A&A* **5**72, A95

Motalebi, F., Udry, S., Gillon, M., Lovis, C., Ségransan, D., Buchhave, L. A., Demory, B. O., Malavolta, L., Dressing, C. D., Sasselov, D., Rice, K., Charbonneau, D., Collier Cameron, A., Latham, D., Molinari, E., Pepe, F., Affer, L., Bonomo, A. S., Cosentino, R., Dumusque, X., Figueira, P., Fiorenzano, A. F. M., Gettel, S., Harutyunyan, A., Haywood, R. D., Johnson, J., Lopez, E., Lopez-Morales, M., Mayor, M., Micela, G., Mortier, A., Nascimbeni, V., Philips, D., Piotto, G., Pollacco, D., Queloz, D., Sozzetti, A., Vanderburg, A., and Watson, C. A.: 2015, *A&A* **5**84, A72

Moutou, C., Lo Curto, G., Mayor, M., Bouchy, F., Benz, W., Lovis, C., Naef, D., Pepe, F., Queloz, D., Santos, N. C., Ségransan, D., Sousa, S. G., and Udry, S.: 2015, *A&A* **5**76, A48

Neuforge-Verheecke, C. and Magain, P.: 1997, *A&A* **3**28, 261

Neveu-VanMalle, M., Queloz, D., Anderson, D. R., Charbonnel, C., Collier Cameron, A., Delrez, L., Gillon, M., Hellier, C., Jehin, E., Lendl, M., Maxted, P. F. L., Pepe, F., Pollacco, D., Ségransan, D., Smalley, B., Smith, A. M. S., Southworth, J., Triaud, A. H. M. J., Udry, S., and West, R. G.: 2014, *A&A* **5**72, A49

Newton, I.: 1687, *Philosophiae Naturalis Principia Mathematica. Auctore Js. Newton*

Ngo, H., Knutson, H. A., Hinkley, S., Bryan, M., Crepp, J. R., Batygin, K., Crossfield, I., Hansen, B., Howard, A. W., Johnson, J. A., Mawet, D., Morton, T. D., Muirhead, P. S., and Wang, J.: 2016, *ApJ* **8**27, 8

Nicholls, C. P., Lebzelter, T., Smette, A., Wolff, B., Hartman, H., Käufl, H.-U., Przybilla, N., Ramsay, S., Uttenthaler, S., Wahlgren, G. M., Bagnulo, S., Hussain, G. A. J., Nieva, M.-F., Seemann, U., and Seifahrt, A.: 2017, *A&A* **5**98, A79

Niedzielski, A., Villaver, E., Nowak, G., Adamów, M., Kowalik, K., Wolszczan, A., Deka-Szymankiewicz, B., Adamczyk, M., and Maciejewski, G.: 2016, *A&A* **5**88, A62

Niedzielski, A., Villaver, E., Wolszczan, A., Adamów, M., Kowalik, K., Maciejewski, G., Nowak, G., García-Hernández, D. A., Deka, B., and Adamczyk, M.: 2015a, *A&A* **5**73, A36

Niedzielski, A., Wolszczan, A., Nowak, G., Adamów, M., Kowalik, K., Maciejewski, G., Deka-Szymankiewicz, B., and Adamczyk, M.: 2015b, *ApJ* **8**03, 1

Nowak, G., Niedzielski, A., Wolszczan, A., Adamów, M., and Maciejewski, G.: 2013, *ApJ* **7**70, 53

Önehag, A., Heiter, U., Gustafsson, B., Piskunov, N., Plez, B., and Reiners, A.: 2012, *A&A* **5**42, A33

Oshagh, M., Santos, N. C., Boisse, I., Boué, G., Montalto, M., Dumusque, X., and Haghighipour, N.: 2013, *A&A* **5**56, A19

Oshagh, M., Santos, N. C., Ehrenreich, D., Haghighipour, N., Figueira, P., Santerne, A., and Montalto, M.: 2014, *A&A* **5**68, A99

Penev, K., Bakos, G. Á., Bayliss, D., Jordán, A., Mohler, M., Zhou, G., Suc, V., Rabus, M., Hartman, J. D., Mancini, L., Béky, B., Csubry, Z., Buchhave, L., Henning, T., Nikolov, N., Csák, B., Brahm, R., Espinoza, N., Conroy, P., Noyes, R. W., Sasselov, D. D., Schmidt, B., Wright, D. J., Tinney, C. G., Addison, B. C., Lázár, J., Papp, I., and Sári, P.: 2013, *AJ* **1**45, 5

Piskunov, N. E., Kupka, F., Ryabchikova, T. A., Weiss, W. W., and Jeffery, C. S.: 1995, *A&A Supp.* **1**12, 525

Pollack, J. B., Hubickyj, O., Bodenheimer, P., Lissauer, J. J., Podolak, M., and Greenzweig, Y.: 1996, *Icarus* **1**24, 62

Quinn, S. N., White, R. J., Latham, D. W., Buchhave, L. A., Torres, G., Stefanik, R. P., Berlind, P., Bieryla, A., Calkins, M. C., Esquerdo, G. A., Fűrész, G., Geary, J. C., and Szentgyorgyi, A. H.: 2014, *ApJ* **7**87, 27

Ramírez, I., Allende Prieto, C., and Lambert, D. L.: 2013, *ApJ* **7**64, 78

Ramírez, I., Fish, J. R., Lambert, D. L., and Allende Prieto, C.: 2012, *ApJ* **7**56, 46

Ramírez, I. and Meléndez, J.: 2005, *ApJ* **6**26, 465

Rodríguez, E., Rodríguez-López, C., López-González, M. J., Amado, P. J., Ocando, S., and Berdiñas, Z. M.: 2016, *MNRAS* **4**57, 1851

Santos, N. C., Adibekyan, V., Figueira, P., Andreasen, D. T., Barros, S. C. C., Delgado-Mena, E., Demangeon, O., Faria, J. P., Oshagh, M., Sousa, S. G., Viana, P. T. P., and Ferreira, A. C. S.: 2017, *ArXiv e-prints*

Santos, N. C., Israelian, G., and Mayor, M.: 2004, *A&A* **4**15, 1153

Santos, N. C., Sousa, S. G., Mortier, A., Neves, V., Adibekyan, V., Tsantaki, M., Delgado Mena, E., Bonfils, X., Israelian, G., Mayor, M., and Udry, S.: 2013, *A&A* **5**56, A150

Sato, B., Izumiura, H., Toyota, E., Kambe, E., Ikoma, M., Omiya, M., Masuda, S., Takeda, Y., Murata, D., Itoh, Y., Ando, H., Yoshida, M., Kokubo, E., and Ida, S.: 2008, *PASJ* **6**0, 539

Sato, B., Omiya, M., Harakawa, H., Izumiura, H., Kambe, E., Takeda, Y., Yoshida, M., Itoh, Y., Ando, H., Kokubo, E., and Ida, S.: 2012, *PASJ* 64

Sato, B., Omiya, M., Harakawa, H., Liu, Y.-J., Izumiura, H., Kambe, E., Takeda, Y., Yoshida, M., Itoh, Y., Ando, H., Kokubo, E., and Ida, S.: 2013a, *PASJ* 65

Sato, B., Omiya, M., Wittenmyer, R. A., Harakawa, H., Nagasawa, M., Izumiura, H., Kambe, E., Takeda, Y., Yoshida, M., Itoh, Y., Ando, H., Kokubo, E., and Ida, S.: 2013b, *ApJ* **7**62, 9

Seager, S.: 2010, *Exoplanets*

Simpson, E. K., Faedi, F., Barros, S. C. C., Brown, D. J. A., Collier Cameron, A., Hebb, L., Pollacco, D., Smalley, B., Todd, I., Butters, O. W., Hébrard, G., McCormac, J., Miller, G. R. M., Santerne, A., Street, R. A., Skillen, I., Triaud, A. H. M. J., Anderson, D. R., Bento, J., Boisse, I., Bouchy, F., Enoch, B., Haswell, C. A., Hellier, C., Holmes, S., Horne, K., Keenan, F. P., Lister, T. A., Maxted, P. F. L., Moulds, V., Moutou, C., Norton, A. J., Parley, N., Pepe, F., Queloz, D., Segransan, D., Smith, A. M. S., Stempels, H. C., Udry, S., Watson, C. A., West, R. G., and Wheatley, P. J.: 2011, *AJ* **1**41, 8

Smiljanic, R., Korn, A. J., Bergemann, M., Frasca, A., Magrini, L., Masseron, T., Pancino, E., Ruchti, G., San Roman, I., Sbordone, L., Sousa, S. G., Tabernero, H., Tautvaišienė, G., Valentini, M., Weber, M., Worley, C. C., Adibekyan, V. Z., Allende Prieto, C., Barisevičius, G., Biazzo, K., Blanco-Cuaresma, S., Bonifacio, P., Bragaglia, A., Caffau, E., Cantat-Gaudin, T., Chorniy, Y., de Laverny, P., Delgado-Mena, E., Donati, P., Duffau, S., Franciosini, E., Friel, E., Geisler, D., González Hernández, J. I., Gruyters, P., Guiglion, G., Hansen, C. J., Heiter, U., Hill, V., Jacobson, H. R., Jofre, P., Jönsson, H., Lanzafame, A. C., Lardo, C., Ludwig, H.-G., Maiorca, E., Mikolaitis, Š., Montes, D., Morel, T., Mucciarelli, A., Muñoz, C., Nordlander, T., Pasquini, L., Puzeras, E., Recio-Blanco, A., Ryde, N., Sacco, G., Santos, N. C., Serenelli, A. M., Sordo, R., Soubiran, C., Spina, L., Steffen, M., Vallenari, A., Van Eck, S., Villanova, S., Gilmore, G., Randich, S., Asplund, M., Binney, J., Drew, J., Feltzing, S., Ferguson, A., Jeffries, R., Micela, G., Negueruela, I., Prusti, T., Rix, H.-W., Alfaro, E., Babusiaux, C., Bensby, T., Blomme, R., Flaccomio, E., François, P., Irwin, M., Koposov, S., Walton, N., Bayo, A., Carraro, G., Costado, M. T., Damiani, F., Edvardsson, B., Hourihane, A., Jackson, R., Lewis, J., Lind, K., Marconi, G., Martayan, C., Monaco, L., Morbidelli, L., Prisinzano, L., and Zaggia, S.: 2014, *A&A* **5**70, A122

Sneden, C. A.: 1973, *Ph.D. thesis*, THE UNIVERSITY OF TEXAS AT AUSTIN.

Soubiran, C., Le Campion, J.-F., Brouillet, N., and Chemin, L.: 2016, *A&A* **5**91, A118

Sousa, S. G., Fernandes, J., Israelian, G., and Santos, N. C.: 2010, *A&A* **5**12, L5

Sousa, S. G., Santos, N. C., Adibekyan, V., Delgado-Mena, E., and Israelian, G.: 2015, *A&A* **5**77, A67

Sousa, S. G., Santos, N. C., Israelian, G., Mayor, M., and Monteiro, M. J. P. F. G.: 2007, *A&A* **4**69, 783

Sousa, S. G., Santos, N. C., Israelian, G., Mayor, M., and Udry, S.: 2011, *A&A* **5**33, A141

Sousa, S. G., Santos, N. C., Mayor, M., Udry, S., Casagrande, L., Israelian, G., Pepe, F., Queloz, D., and Monteiro, M. J. P. F. G.: 2008, *A&A* **4**87, 373

Takeda, Y., Sato, B., and Murata, D.: 2008, *PASJ* **6**0, 781

Torres, G., Andersen, J., and Giménez, A.: 2010, *Astronomy and Astrophysics Reviews* **1**8, 67

Torres, G., Winn, J. N., and Holman, M. J.: 2008, *ApJ* **6**77, 1324

Tsantaki, M., Andreasen, D. T., Teixeira, G. D. C., Sousa, S. G., Santos, N. C., Delgado-Mena, E., and Bruzual, G.: 2017, *MNRAS* **5**55, A150

Tsantaki, M., Sousa, S. G., Adibekyan, V. Z., Santos, N. C., Mortier, A., and Israelian, G.: 2013, *A&A* **5**55, A150

Valenti, J. A. and Fischer, D. A.: 2005, *ApJS* **1**59, 141

Valenti, J. A. and Piskunov, N.: 1996, *A&A Supp.* **1**18, 595

Vanderburg, A., Montet, B. T., Johnson, J. A., Buchhave, L. A., Zeng, L., Pepe, F., Collier Cameron, A., Latham, D. W., Molinari, E., Udry, S., Lovis, C., Matthews, J. M., Cameron, C., Law, N., Bowler, B. P., Angus, R., Baranec, C., Bieryla, A., Boschin, W., Charbonneau, D., Cosentino, R., Dumusque, X., Figueira, P., Guenther, D. B., Harutyunyan, A., Hellier, C., Kuschnig, R., Lopez-Morales, M., Mayor, M., Micela, G., Moffat, A. F. J., Pedani, M., Phillips, D. F., Piotto, G., Pollacco, D., Queloz, D., Rice, K., Riddle, R., Rowe, J. F., Rucinski, S. M., Sasselov, D., Ségransan, D., Sozzetti, A., Szentgyorgyi, A., Watson, C., and Weiss, W. W.: 2015, *ApJ* **8**00, 59

West, R. G., Hellier, C., Almenara, J.-M., Anderson, D. R., Barros, S. C. C., Bouchy, F., Brown, D. J. A., Collier Cameron, A., Deleuil, M., Delrez, L., Doyle, A. P., Faedi, F., Fumel, A., Gillon, M., Gómez Maqueo Chew, Y., Hébrard, G., Jehin, E., Lendl, M., Maxted, P. F. L., Pepe, F., Pollacco, D., Queloz, D., Ségransan, D., Smalley, B., Smith, A. M. S., Southworth, J., Triaud, A. H. M. J., and Udry, S.: 2016, *A&A* **5**85, A126

Wilson, P. A., Hébrard, G., Santos, N. C., Sahlmann, J., Montagnier, G., Astudillo-Defru, N., Boisse, I., Bouchy, F., Rey, J., Arnold, L., Bonfils, X., Bourrier, V., Courcol, B., Deleuil, M., Delfosse, X., Díaz, R. F., Ehrenreich, D., Forveille, T., Moutou, C., Pepe, F., Santerne, A., Ségransan, D., and Udry, S.: 2016, *A&A* **5**88, A144

Wolszczan, A. and Frail, D. A.: 1992, *Nature* **3**55, 145

Zhou, G., Bayliss, D., Penev, K., Bakos, G. Á., Hartman, J. D., Jordán, A., Mancini, L., Mohler, M., Csubry, Z., Ciceri, S., Brahm, R., Rabus, M., Buchhave, L., Henning, T., Suc, V., Espinoza, N., Béky, B., Noyes, R. W., Schmidt, B., Butler, R. P., Shectman, S., Thompson, I., Crane, J., Sato, B., Csák, B., Lázár, J., Papp, I., Sári, P., and Nikolov, N.: 2014, *AJ* **1**47, 144

Zieliński, P., Niedzielski, A., Wolszczan, A., Adamów, M., and Nowak, G.: 2012, *A&A* **5**47, A91