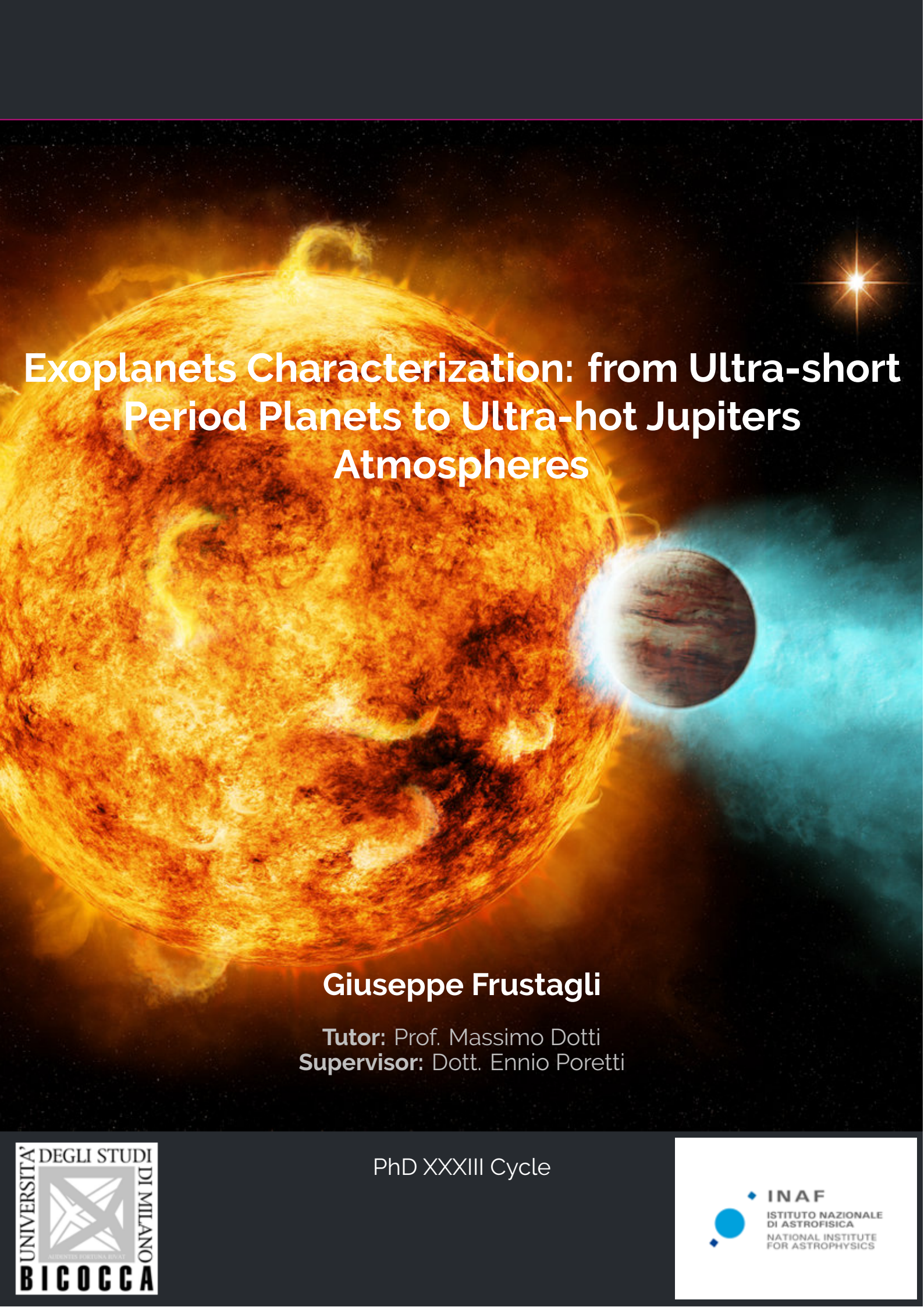




Exoplanets Characterization: from Ultra-short Period Planets to Ultra-hot Jupiters Atmospheres

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Abstract

The discovery of planets orbiting around stars other than the Sun is by far the most relevant event in the galactic astrophysics of the last two decades. Since the discovery of the first exoplanet in 1995, the number of exoplanets discovered grew fast and we currently know more than 4,000 exoplanets, very diverse in dimension and distance from parent stars and also in factors as temperature, mass, density. The diversity of exoplanets is a key factor to understand more about the formation of planetary systems and in particular the formation of the Solar System and our planet, the Earth. This is the reason why observational exoplanetary science is currently focusing on two different fields: i) the characterization of exoplanets, trying to determine the radius, the mass, the density and the bulk composition of the objects observed, and ii) the characterization of their atmospheres, establishing the elements that the atmosphere of a planet supports and the mechanisms that drive the atmospheric processes.

Characterization of Exoplanets

Photometry with the transit method has arguably been the most successful exoplanet discovery method to date. The method's strength is the rich set of parameters that can be obtained from transiting planets, in particular in combination with RV observations.

In this framework, one of the most prolific groups is the HARPS-N Guaranteed Time Observations (GTO) Consortium, that makes use of the high resolution ($R = 115,000$) and extreme stability of the HARPS-N spectrograph (Cosentino et al., 2012), installed on the Telescopio Nazionale Galileo (TNG), to characterize and discover exoplanets by combining transits and RV methods. As a collaborator of this group, I studied a candidate planet discovered by K2 Campaign 16, HD 80653 b, a super-Earth planet ($R = 1.608 \pm 0.071 R_{\oplus}$) transiting the star on a short period orbit ($P = 0.719573 \pm 0.000021$ d). It belongs to a peculiar class of exoplanets: the Ultra-Short Period (USP) planets, objects that orbit their stars with extremely short periods, smaller than about $2R_{\oplus}$ and compositions similar to that of the Earth (Winn et al., 2018).

From our radial velocity measurements, we constrained the mass of HD 80653 b to

$M = 5.60 \pm 0.43 M_{\oplus}$ and derived the bulk density ($\rho = 7.5 \pm 1.1 \text{ g cm}^3$) of the planet, consistent with an Earth-like rocky/iron composition and no thick atmosphere. The results have been summarized in a paper submitted to a peer-review journal (Frustagli et al., 2020). Furthermore, we continued the RV monitoring of the system, extending the time baseline, and we were able to tighten the constraints on the orbital parameters and mass of a long period companion of the USP super-Earth. The observations are currently ongoing, but the new data suggest that the companion has a period of $P_c = 956.39^{+20.80}_{-19.62} \text{ d}$, with a high eccentricity $e = 0.836 \pm 0.011$, and a mass limit of $M_c \sin i_c = 5.16^{+0.24}_{-0.22} M_J$. The analysis will be refined and the results will be reported in a paper (Frustagli et al., in prep.).

Another realm of exoplanet discovery that is often overlooked is discovering young (e.g., $< 1 \text{ Gyr}$) exoplanets that will help to probe the main causes of planetary evolution and to fill a key gap in our knowledge of exoplanet history. The combination of several factors such as increased activity, rotation rates and relative proximity to neighbouring stars (e.g., Cegla et al., 2019) can result in periodic stellar variability similar to that produced by planetary signals in both period and intensity, representing then significant challenges for discovery. Despite the difficulties in dealing with the identification of planetary signals in presence of the very high activity levels of their hosts, the Global Architecture of Planetary Systems (GAPS) Young Objects (YO) program objective is the study of the origin of planetary systems shaped by the different stages of orbital evolution, through the determination of the architectures and orbital parameters of hot and warm Jupiters and hot Neptunes around young ($\leq 50 \text{ Myr}$) and intermediate-age ($600 - 700 \text{ Myr}$) stars.

Only a small fraction of exoplanets are transiting planets, therefore, despite the potentially strong limitation to the search for planets represented by high levels of magnetic activity seen at young ages, RV blind surveys are an ambitious and challenging, but necessary task to find and characterize new exoplanets and to test the possible differences in the frequency of exoplanets with age. In the framework of GAPS YO program, I studied TYC 4610-1318-1 (YO-09, hereafter), a young K1 star of the Cepheus open cluster. I analyzed the periodograms of the RV and activity indicators of the time series for this object and I used `PyORBIT` in the attempt to find a possible planetary signal hidden in the RV time series. My analyses resulted in a null detection of significant signals, with the conclusion that there is no strong evidence for a model with at least one planet, even though a planet in this system cannot be completely excluded.

Characterization of Atmospheres

Ultra-hot Jupiters are excellent laboratories for the study of exoplanetary atmospheres. Sodium, due to its large cross-section and to the fact it is in the wavelength range of most optical spectrographs, is the most studied element, but new interesting features begin to be analyzed. Lines of iron, titanium, magnesium, but also chromium, scandium and yttrium have been found in the high resolution transmission spectra of the hottest planets (e.g., KELT-9; b Hoeijmakers et al., 2019). The two ultra-hot Jupiters KELT-9 b and KELT-20 b were observed in the framework of the GAPS Atmosphere program.

I explored more in detail the transit spectroscopy method, creating two routines. The first routine follows previous approaches for high-resolution spectroscopy (e.g., Wyttenbach et al., 2017), but it is able to detect weak spectral lines such as those of magnesium, by co-adding the lines in the velocities space. Following this procedure, I analyzed the high-resolution spectra of KELT-9 b and KELT-20 b, obtaining their transmission spectra. I detected significant absorption in the transmission spectrum for Na, H, Fe and Mg I, and I certified their planetary nature by using the 2D tomographic technique.

The second routine extracts the high-resolution transmission spectra of exoplanets and cross-correlates them with theoretical transmission spectra models. I analyzed the high-resolution spectra of KELT-20 b and with the cross-correlation technique I confirmed previous detections of Fe I, Fe II, and Na I. In particular, the planetary atmospheric signal during transit shows an overall blueshift of $\approx 10 \text{ km s}^{-1}$. I also explored the possible variation in the structure and position of the Fe I signal in different transits.

As the study of atmospheric signatures at high spectral resolution in the transmission spectra becomes more and more important, understanding how to separate the signal due to the planetary atmosphere from other effects measured by the spectrographs is of crucial importance, because the differential techniques we use are sensitive to all the variations that can appear in the form of spectral lines in times that characterize the transit. Among the effects that can modify the shape of an atmospheric signal or that can create “false signals”, there are the effects due to Earth’s atmosphere behaviour, triggered by natural phenomena or artificial activities in proximity of the observing facilities. Sodium is a widespread element in Earth’s atmosphere. A few studies (e.g., Slipher, 1929; Slanger et al., 2005) showed that several chemical reactions in the mesosphere can cause a small radiation due to the telluric emission of the sodium doublet and currently we do not know whether this radiation can influence our analysis of the exoplanets atmospheres. I investigated this issue, using

more than 4,000 spectra of the sky background from the archive of the TNG. The goal was to study possible variations of the sky emission with time, airmass and telescope's pointing direction.

Before analyzing the spectra I put some constraints on my data, in order to exclude spectra in which the sky sodium doublet emission was diluted in the instrumental noise or to exclude processes not due to night sky emission. I kept only the spectra in which the intensity of the sodium doublet lines was stronger than a noise threshold and the data for which the solar elevation angle was above the threshold of -18° , in order to exclude data affected by twilight effects. In this way, the number of spectra significantly decreased to about 2,600. This did not allow me to draw firm conclusions about the results, however it was possible to point out a few facts. First, my analysis shows that there is not a clear evidence of strong variations with airmass. Second, no privileged direction when pointing the telescope emerges, but the distribution of emission is homogeneous in the sky. Third, from the analysis of the Na doublet ratio intensity against time, there is an evidence that the emission has a minimum in summer and maximum in autumn.

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Part I

Planet Characterization

Introduction

” The Earth is the only world known so far to harbor life. There is nowhere else, at least in the near future, to which our species could migrate. Visit, yes. Settle, not yet. Like it or not, for the moment the Earth is where we make our stand.

— Carl Sagan
(Pale Blue Dot: A Vision of the Human Future
in Space)

Since ancient times, humankind has wondered about the existence of other forms of life in the Universe. Starting from the Greeks, we have always speculated, first philosophically and then looking for scientific evidences, about the existence of other planetary systems which are able to support life.

At looking back history, the atomists first and then Epicurus opened the door to the concept of a Universe populated by numerous worlds, but the idea of a unique world, portrayed by Plato and Aristotle, had a much bigger impact.

“There are infinite worlds both like and unlike this world of ours. We must believe that in all worlds there are living creatures and planets and other things we see in this world” (Epicurus, ~ 300 a.C.)

In the Middle Age, the topic of the plurality of worlds was the subject of debate for Albert Magnus and his disciple Thomas Aquinas. Following the Copernican revolution, Giordano Bruno became a strong supporter of this idea.

“There are countless suns and countless earths all rotating around their suns in exactly the same way as the seven planets of our system... The countless worlds in the universe are no worse and no less inhabited than our Earth” (Giordano Bruno, 1584)

Following Descartes ideas, Bovier de Fontanelle in his *Entretiens sur la pluralité des mondes* (1686) and Christiaan Huygens in his *Cosmotheoros* (1698) supported the possibility of an infinite number of possible worlds.

“For then why may not every one of these Stars or Suns have as great a Retinue as our Sun, of planets, with their moons, to wait upon them? Nay, there’s Manifest reason why they should” (Christiaan Huygens, 1698)

The year 1687 saw the start of a new era. The publication by Isaac Newton of the *Philosophiae naturalis principia mathematica* laid down the basis of the laws of universal gravitation and opened the way for the nebular theory.

Immanuel Kant in his *Allgemeine Naturgeschichte und Theorie des Himmels* (1755) and Pierre-Simone de Laplace with his work *Exposition du système du monde* (1796) proposed a model for the origins of the Solar System based on the idea of the collapse of a rotating cloud, which flattens into a disk, within which planets subsequently formed.

Today, at the beginning of the third millennium, we are able to verify if our speculations and fantasies about other worlds are real. We have started to speculate about our origins. Are we just one of many instances of life, evolving on a common type of planet? Or are we unique, born in a very special place and under very extraordinary circumstances? These are still unanswered questions, but at this point in our evolution, we have the technology to address them and to be able to answer them.

1.0.1 A Brief Recap of Exoplanetary Astronomy

The discovery of the planet 51 Peg b (Mayor and Queloz, 1995) opened a completely new field of observative astronomy: the systematic study of planetary systems, their dynamical properties, formation and evolution. Although our possibilities to operate in this field are fairly recent, the existence of exoplanets was considered more than plausible for a long time. Scientific speculations of this kind go back to the beginning of the 18th century. Isaac Newton advanced the first documented hypothesis of the existence of these celestial bodies in the General Scholium that concluded his *Principia* (1713): “And if the fixed Stars are the centers of other like systems, these, being form’d by the like wise counsel, must be all subject to the dominion of One”.

News of a few supposed discoveries followed for all the 19th century, but the observation techniques of the time were not sufficiently accurate and technologically advanced to confirm them undoubtedly. Some of the earliest involve the binary star 70 Ophiuchi. In 1855, Captain W. S. Jacobs from the East India Madras Observatory reported that orbital anomalies in the orbit of the binary star 70 Ophiuchi made it “highly probable” that there was a “planetary body” in this system. Between

1896 and 1899, T. J. J. See, astronomer of the Chicago University, and the Naval Observatory of the United States, stated that those anomalies were due to the presence of an obscure companion with an orbital period of 36 years, connected to one of the two stars of the binary system.

F. R. Moulton opposed to this hypothesis, and in 1899 published new analysis of the data, stating that a three-body system with those orbital parameters as described by See would have been highly unstable.

Another claim of the discovery of the first extrasolar planet was in 1963. P. van de Kamp announced he discovered, using astrometric observations, an invisible companion around the Barnard's star, with a mass 1.6 times the mass of Jupiter. Ten years later Hershey demonstrated that the planet did not exist, and the anomalous movements of the star were due to a systematic error in the mechanics of the telescope used by van de Kamp.

In 1984, a new discovery opened a new horizon in exoplanetary science: a circumbinary disk around the star β Pictoris was observed (Smith and Terrile, 1984). Nowadays, almost 30 years later, we know of hundreds of circumbinary disks, places where planets are forming or residuals of their formation.

A few years later, in 1989, Latham announced the discovery of a substellar companion around the star HD 114762. The planet discovered (HD 114762 b) has a mass $\sim 10 M_J$, very close to the limit of the deuterium burning, and so different from the common sense of a planet.

In 1992, two earth-size planets orbiting around PSR 1257+12 were detected (Wolszczan and Frail, 1992). In the same year, G. Walker announced that the radial velocity oscillations of the star γ Cephei could be due to the presence of a planet of mass $\sim 2 M_J$ (Walker et al., 1992).

The first confirmed and indubitable discovery of an exoplanet dates back to 1995: M. Mayor and D. Queloz of the University of Geneva announced the first detection of an exoplanet with a mass close to that of Jupiter orbiting 51 Peg, an ordinary Main Sequence star (Mayor and Queloz, 1995). Few days later, G. Marcy and R. Butler confirmed the existence of the planet and stated that the variation of the radial velocity could not be due to stellar activity (Marcy and Butler, 1995). For this discovery, M. Mayor and D. Queloz were awarded the 2019 Nobel Prize in Physics.

This discovery signed the beginning of the new era of exoplanetary science, an era that relies on the fast technological progress in the realization of observational instruments. The improvements in the field of high-resolution spectroscopy and high precision photometry lead us to discover a great number of exoplanets (see

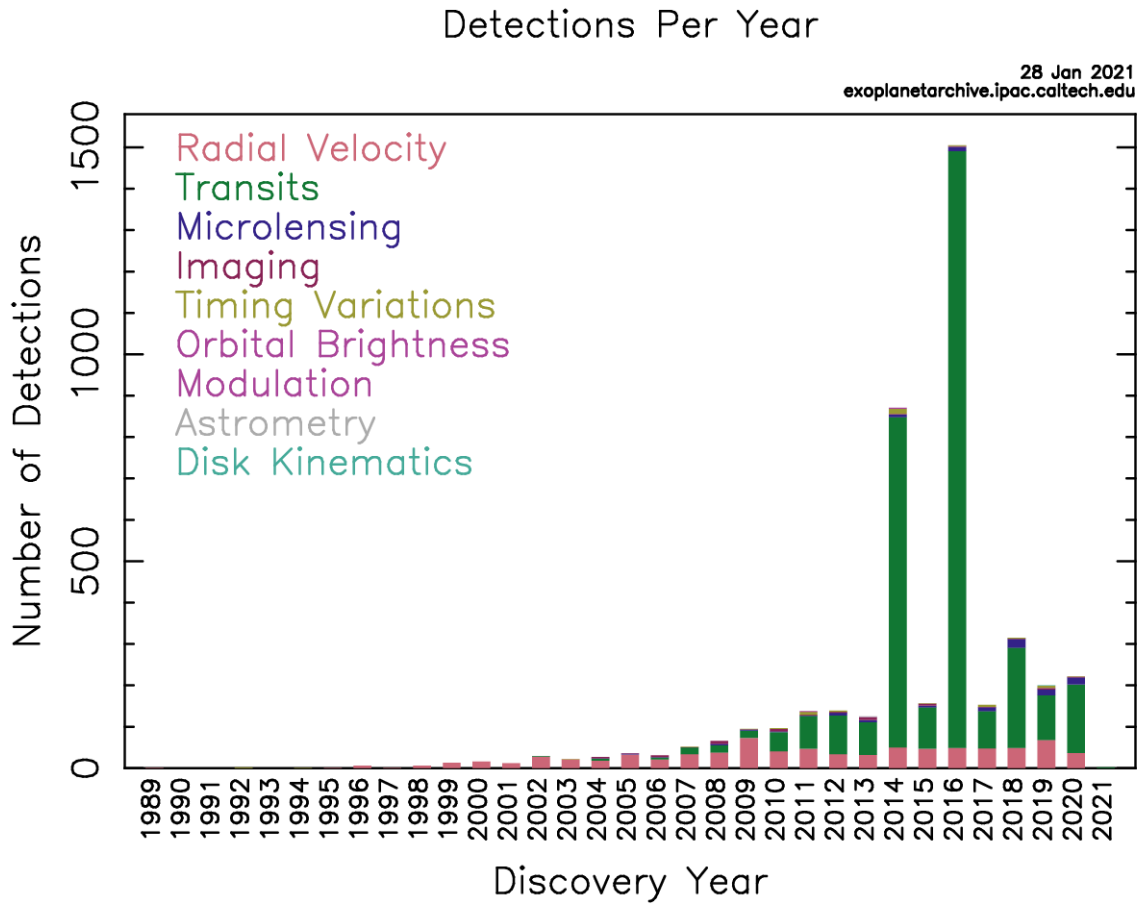


Fig. 1.1: Number of extrasolar planet discoveries per year through January 2021, with colors indicating method of detection. The two green peaks indicate the two major announces of planetary candidates discovery from the Kepler mission.

Fig. 1.1): on January 28th, 2021, we know 4680 extrasolar planets, organized in 3457 planetary systems¹.

1.1 Main Discovery Methods

Discovery methods to find exoplanets are different and sometimes complementary. Combining some of these methods allows us to obtain more information about the planet and to determine its properties and its environment. In this Section, the main detection methods used to discover exoplanets, radial velocity and transit methods, are described in a general manner.

¹<http://exoplanet.eu/catalog.php>

1.1.1 Radial Velocimetry

From Earth it is impossible to observe the radial location of the star along the line of sight, because, by definition, the motion projected on the sky is non-existent. It is, however, possible to measure the radial velocity of the star using spectroscopy, by estimating in the radial velocity curve (Fig. 1.2) eventual periodicities that can be caused by a planet.

By using Kepler's Second Law (the Law of Areas), which is expressed, for an elliptical orbit of period P , semi-major axis a , and eccentricity e , by the equation:

$$r^2 \frac{d\nu}{dt} = \frac{2\pi}{P} a^2 \sqrt{1 - e^2} \quad (1.1)$$

and deriving the expression of the position of the star on the line of sight with respect to time, the result is the equation for the stellar radial velocity:

$$v_r = \frac{2\pi}{P} \frac{a_\star \sin i}{\sqrt{1 - e^2}} [\cos(\nu + \omega) + e \cos \omega] \quad (1.2)$$

where ν is the angular position of the object relative to an origin given by the orbit's periastron and ω is the rotation angle around the normal to the plane of the orbit. In the two-body case, it is thus possible to derive an equation that is a function of the mass of the planet and the mass of the star. Using Kepler's Third Law, applied to the system consisting of the star and the planet, we obtain:

$$\frac{a^3}{(M_\star + M_p)} = \frac{P^2 G}{4\pi^2} \quad (1.3)$$

where $a = a_\star + a_p$ and $M_\star a_\star = M_p a_p$. The result is:

$$a_\star^3 = \frac{P^2 G}{4\pi^2} \frac{M_p^3}{(M_\star + M_p)^2} \quad (1.4)$$

and using Eq.1.2 and Eq.1.4, we obtain:

$$\frac{(M_p \sin i)^3}{(M_\star + M_p)^2} = \frac{P}{2\pi G} K_\star^3 (1 - e^2)^{\frac{3}{2}} \quad (1.5)$$

where we set:

$$K_{\star} = \frac{2\pi}{P} \frac{a_{\star} \sin i}{\sqrt{1-e^2}} \quad (1.6)$$

Equation 1.5 shows that measuring the radial velocity does not allow us to simultaneously determine $M_{\star}$ and M_p , but, assuming that the mass of the planet is negligible relative to the mass of the star, and also that the mass of the star may be estimated by some other means, then an estimate of the product $M_p \sin(i)$ is:

$$M_p \sin i \approx \left(\frac{P}{2\pi G}\right)^{\frac{1}{3}} K_{\star} M_{\star}^{\frac{2}{3}} \sqrt{1-e^2} \quad (1.7)$$

Measurements of radial velocities only allow to derive a minimum mass for the planet, because it is not possible to derive equations that omit the system's angle of inclination. Only in the specific case in which the planet is seen edge on we can determine the individual masses of the system's planets. Note also that by assuming that planetary systems have a random orientation relative to the plane of the sky, it is possible to ignore the orientation statistically, and obtain a mass distribution for the planets as a whole.

Neglecting the mass of the planet relative to the mass of the star, we may also deduce, from Kepler's Third Law, the semi-major axis of the planets orbit around the centre of gravity as a function of the orbital period and of the mass of the star:

$$a_p = \left(\frac{G}{4\pi^2}\right)^{\frac{1}{3}} P^{\frac{2}{3}} M_{\star}^{\frac{1}{3}} \quad (1.8)$$

Measuring the radial velocity of a star to determine the presence of possible planets is a method that is biased towards massive objects with a small orbital radius, since $K_{\star}$ is proportional to the mass of the planet and to $P^{-1/3}$.

This technique is very effective but presents a few disadvantages. As with astrometry, in order to detect long-period objects the method requires regular observations and an instrumental stability monitored over time.

It does not allow us to observe systems that are viewed face-on.

Finally, it is necessary to mention that in the case of multiple systems, the radial velocity, taken overall, consists of the sum of the different contributions of the planets, and of their periods of revolution. The detection of multiple systems is therefore carried out by analyzing the components of the radial velocity by subtracting the principal component, followed by the analysis of the residuals until the measurements noise is reached.

The measurement of the radial velocity of a star is based on the Doppler-Fizeau effect: any observer who receives a wave emitted at the frequency ν by a source in

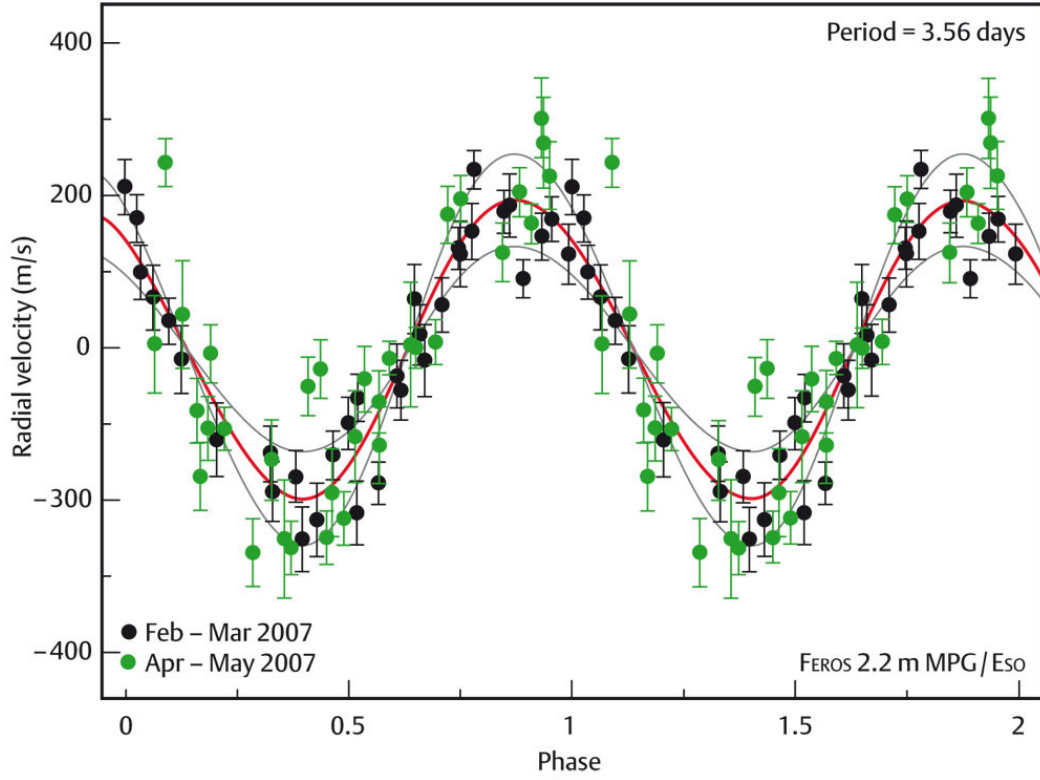


Fig. 1.2.: Example of radial velocity oscillation of TW Hydrae as observed in 2007. Credit: MPIA (<http://www.mpia.de>)

motion, detects it at the frequency $\nu + \delta\nu$, where $\delta\nu$ is positive (greater frequency, thus shorter wavelength) if the object is approaching, and negative (lower frequency and greater wavelength) if the object is receding (Fig. 1.3).

In the relativistic expression of the Doppler-Fizeau effect, the wavelength observed is given as a function of the wavelength of the source by the equation:

$$\lambda_{obs} = \lambda_{source} \sqrt{\frac{1 + \frac{v_r}{c}}{1 - \frac{v_r}{c}}} \quad (1.9)$$

where v_r is the radial velocity of the source, positive when the object is receding, and c is the speed of light in vacuum. From this expression we can derive the relative shift in wavelength (or frequency) as:

$$\frac{\Delta\lambda}{\lambda} = \frac{v_r}{c} = -\frac{\Delta\nu}{\nu} \quad (1.10)$$

Measurements of the radial velocity of a star is therefore carried out by high-resolution spectroscopy. The spectrograph resolves the radiation from the star into

its different components and allows the measurement of the shift in wavelength by observing the overall shift in the absorption lines in the spectrum.

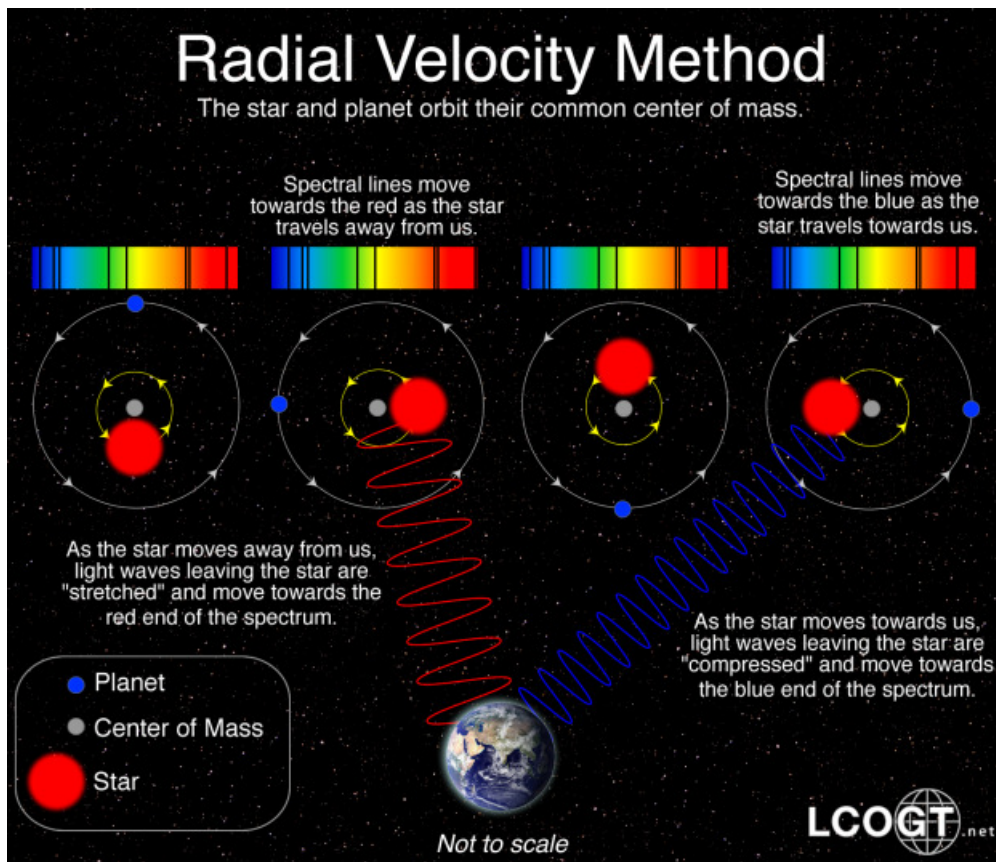


Fig. 1.3.: How the radial velocity method works. Credit: Las Cumbres Observatory

The best current instrument, the Echelle SPectrograph for Rocky Exoplanets and Stable Spectroscopic Observations (ESPRESSO, Pepe et al., 2014; Pepe et al., 2021), allows us to obtain a radial velocity to an accuracy better than 10 cm s^{-1} , and a stability that spans over a period of several years.

1.1.1.1. Limit for the RV precision

Typical velocities of the star's motion are several ten m s^{-1} for giant planets (12 m s^{-1} for Jupiter in the solar system), and several cm s^{-1} for terrestrial planets with masses similar to Earth (9 cm s^{-1} for Earth around the Sun). Therefore, it is worth wondering whether improved instruments with higher resolution, higher sampling, greater stability and more precise wavelength calibration will ultimately be able to detect analogs of the Earth. The RV precision achievable in a stellar spectrum

depends on the number of photons (or the signal-to-noise ratio, SNR) and the amount of spectroscopic information, that is, the presence of spectral features (e.g., Connes, 1985; Bouchy et al., 2001). The fundamental limit that can be achieved from an observation of any given star is the RV photon noise. Line broadening, in particular by stellar rotation, and activity effects are additional factors that can deteriorate the RV precision. Line broadening diminishes the amount of spectroscopic features and its effect can be compensated with longer exposures (leading to higher SNR). Stellar activity is a potential source of additional noise that must be addressed by modeling the effect using additional information (e.g., Dumusque, 2018; Collier Cameron et al., 2019). Considering the spectrograph measuring the RV as perfect, assuming that a spectrum experiences a differential shift relative to a noise-free reference spectrum and that the act of measurement introduces no noise, Bouchy et al. (2001) calculated the error on the measured RV

$$\delta v = \frac{c}{\sqrt{\sum_i W(i)}} \quad (1.11)$$

where $W(i)$ is the optimal weight function to be given to a pixel i when calculating the RV, given by

$$W(i) = \frac{\lambda^2 (\delta A_0(i)/\delta \lambda)^2}{A_0(i) + \sigma_D^2} \quad (1.12)$$

with σ_D representing the readout noise. In these equations, the weight of a pixel, for a given λ , depends on the absolute value of the slope of the spectrum ($\delta A/\delta \lambda$). Therefore, our ability to measure the position of a spectrum relative to the reference spectrum depends on the slope of its lines.

Applying this formalism and assuming a Gaussian-shaped line, the RV precision can be calculated as

$$\sigma_{RV} = \frac{(\pi \ln 2)^{-1/4}}{2} \frac{\sqrt{FWHM}}{SNR} \frac{PXLSC}{C} F(C_{\text{eff}}) [m \cdot s^{-1}] \quad (1.13)$$

where C is the contrast of the Gaussian line, SNR the signal-to-noise ratio of the spectrum, PXLSC the pixel scale of the spectrograph (i.e., the dimension of the pixel as measured in velocity), and $F(C_{\text{eff}})$ is a polynomial function of the effective contrast $C_{\text{eff}} = C/(1 + \sigma_D^2/A_0)$. Therefore, the RV precision increases linearly with the SNR and it is proportional to the contrast C of a line, and inversely proportional to the square root of the FWHM of the line. From Eq. 1.13, it is clear that the broadening of spectral lines, caused either by stellar rotation or instrumental spectral resolution, can have a strong influence on radial velocity precision. An increase in rotational velocity, or decrease in resolution, simultaneously increases the FWHM and decreases the contrast since the total equivalent width must be conserved ($C \sim 1/FWHM$).

It becomes also evident that the global Doppler information content depends both on the intrinsic line richness (density and depth) and on the SNR of the spectrum. In general, the spectral richness increases towards the blue visible region, making it the natural choice for RV measurements of FGK stars, which also emit most of their light at these wavelengths. Only the use of thousands of lines in stellar and wavelength calibration spectra makes it possible to reach the high levels of precision required to achieve radial velocity measurements at the m s^{-1} level.

Two different methods are used to gather precise calibration of RV measurements, simultaneously tracking instrumental changes by comparison with a set of stable reference lines. The Iodine cell method inserts in the input stellar beam an iodine cell to superimpose stable absorption lines on the incoming starlight (e.g., Butler et al., 1996). Iodine cells have demonstrated a long-term stability at the $\sim 12 \text{ m s}^{-1}$ level, but with some intrinsic limitations. Slight short-term or long-term variations in iodine pressure may affect the overall shape of the iodine spectrum, made of numerous, Doppler-broadened and overlapping molecular transitions and the usable wavelength range is limited to $\sim 1200 \text{ \AA}$ (from 5000 to 6200 $\text{\AA}$), which makes it impossible to use the stellar Doppler information in other spectral regions. Moreover, the Doppler information content of the iodine itself is a function of the achieved SNR in the continuum, determined by the stellar flux in the case of star and iodine exposures and as a consequence, high-SNR observations are required, setting strong constraints on the target magnitude and/or exposure time.

The second method, the simultaneous wavelength reference method, makes use of an optical fiber for the starlight, and a second fiber illuminated by a stable laboratory source (e.g., Baranne et al., 1996), usually a ThAr hollow cathode lamp. ThAr lamps have also demonstrated a longterm stability at the $\sim 12 \text{ m s}^{-1}$ level and cover a larger spectral range than iodine. Their spectra show, however, blends and a large dynamic range in line intensities which complicate the precise measurement of line positions. They also have a limited lifetime, experiencing aging effects that induce changes in line intensities and wavelength shifts. Nonetheless, these can be corrected to high precision and ThAr lamps have demonstrated a long-term and lamp-to-lamp stability at the $\sim 30 \text{ cm s}^{-1}$ level.

The ideal calibration source for high-precision RV measurements remains to be invented. A promising new approach is the development of the laser comb technology (e.g., Wu, 2017)), that deliver an extremely regular pattern of equally-spaced emission lines (in frequency) over a potentially broad wavelength range. Their main advantage is that line wavelengths can be precisely controlled by locking the comb to an atomic clock, creating a direct link between the most accurate frequency references ever developed and optical frequencies, overcoming the reliability problems encountered

with other calibration sources. However, these tools still have to be adapted to high-resolution astronomical spectrographs. The rapid development of this technology should lead to satisfactory solutions, making laser combs the calibrator of choice for ultra-high-precision radial velocity measurements.

1.1.2 Planetary Transits

A planetary system observed edge-on is a very interesting case (Fig. 1.4). The planets may, in fact, transit the star and cause a small drop in brightness of the star's flux (Fig. 1.5). The amplitude of the extinction enables us to obtain the diameter of the planet and the distance between two different transits enables us to derive the planet's orbital period and hence its distance from the star.

One of the most important features of this method is that the observation of a planetary transit is possible only if the planet is seen very close to edge-on.

The total transit duration is heavily dependent on the impact parameter, defined

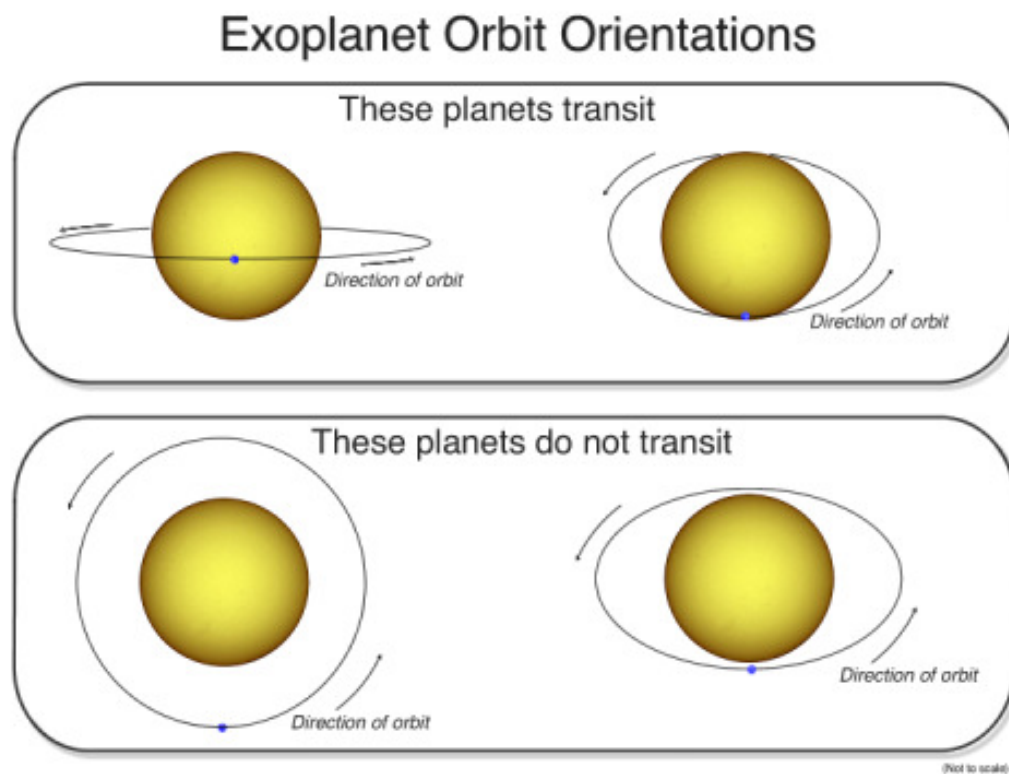


Fig. 1.4.: Examples of planet's orbit orientations. This method only works for star-planet systems that have orbits aligned in such a way that, as seen from Earth, the planet travels between us and the star and blocks some of the light from the star. Credit: Las Cumbres Observatory

as the sky-projected distance between the centre of the stellar disc and the centre of the planetary disc at conjunction (i.e, the point in the orbit where two objects are most closely aligned, as viewed from Earth). A transit occurs when the impact parameter of the planets orbit with respect to the star in units of the host radius,

$$b = \frac{a \cos i}{R} \frac{1 - e^2}{1 + e \sin \omega_\star} \quad (1.14)$$

is smaller than the sum of the normalized radii, $b \leq 1 + k$, where $k = R_p/R_\star$. Note that the impact parameter is related to the inclination i of the orbit . Integrating over i , assuming isotropic orbit and thus a uniform distribution of $\cos i$ yields the transit probability,

$$P_{transit} = \frac{R_p + R_\star}{a} \frac{1 + e \sin \omega_\star}{1 - e^2} \quad (1.15)$$

that for a circular orbit and assuming $k \ll 1$, reduces to the expression

$$P_{transit} \sim \frac{R_\star}{a} \quad (1.16)$$

The probability decreases rapidly with the planet's orbital distance (and thus period). Detection of planets by observing their transits on a star will be more favorable for planets at short distances from their parent star.

To go further this inconvenience of low probability, we observe lots of stars: in this way, statistically, we can observe transiting planets. If we suppose the inclination of planetary systems respect to our line of sight to be casual, about 10 percent of planets orbiting Solar-like star at 0.05 AU will have a visible transit. If the orbit is at 5 AU, probability decreases to 0.1 percent.

The duration of the transit can be quantified with its full-width at half maximum, which is roughly the time interval T between the two points where the center of the planet appears to touch the edges of the star. The result is

$$T \simeq T_{eq} \sqrt{1 - b^2} \quad (1.17)$$

where is useful to define the equatorial crossing time (i.e. the transit duration for $b = 0$),

$$T_{eq} = \frac{R_\star P}{\pi a} = f_{tr} P \simeq \left(\frac{3P}{\pi^2 G \rho_\star} \right)^{\frac{1}{3}} \quad (1.18)$$

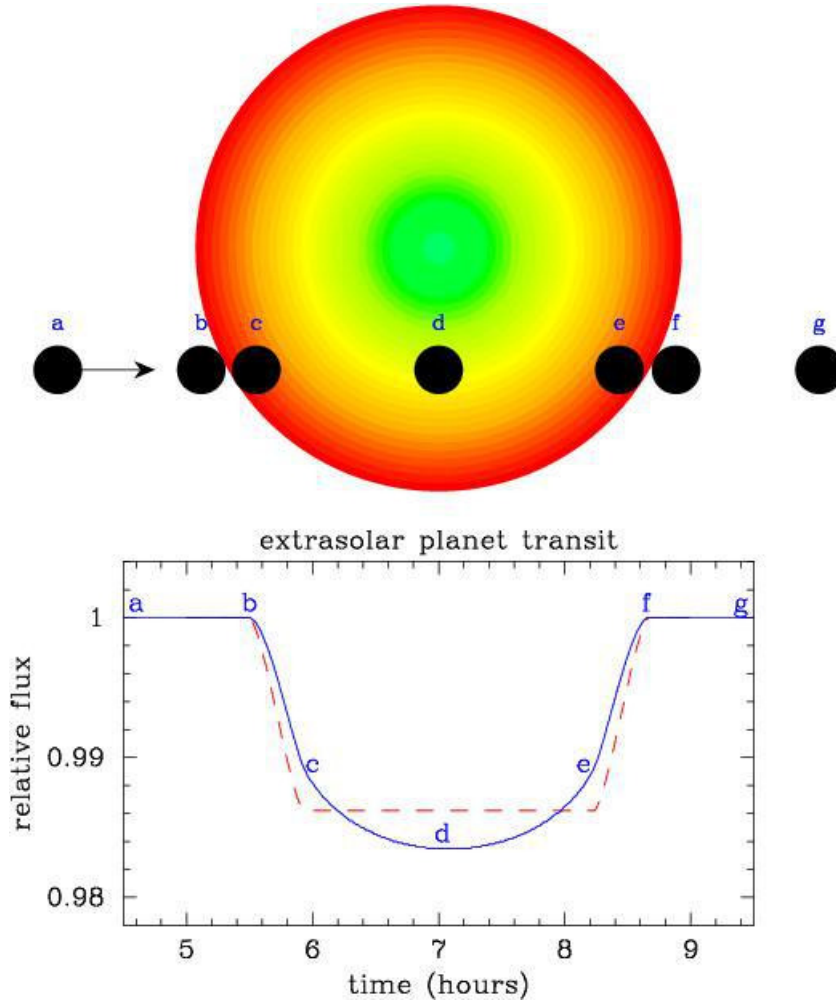


Fig. 1.5.: The principle of the transit method.

Here $\rho_\star$ is the mean density of the host star, and $f_{tr} = P/\pi a = P_{transit}/\pi$ is the transit duty cycle, or the fraction of planet orbit in transit. The last equality assumes $M_p \ll M_\star$.

The dimensions of the transiting object, known as transit depth δ , is defined by:

$$\delta = \frac{\Delta F}{F} = \frac{F_{nottransit} - F_{transit}}{F_{nottransit}} = \left(\frac{R_p}{R_\star}\right)^2 \quad (1.19)$$

The transit of a giant planet like Jupiter causes a photometric extinction of 1 percent and that of a terrestrial planet like Earth an extinction of 0.01 percent. To detect a planet by the transit method, it is then necessary a photometric accuracy of roughly a fraction of one percent for giant planets and around some 10^{-5} for terrestrial planets.

Although the detection of giant planets is possible from the ground, where one may achieve accuracies of around 10^{-3} , limited by atmospheric turbulence, the detection of earthlike planets may only be contemplated from space.

This method's potential is not limited to just the identification of planetary candidates. In fact, when combined with the radial-velocity method, detection of a transit enables the observer to derive the size of the object (i.e. the amplitude of the extinction), its exact mass (by measurement of the radial velocities) and the density of the object, thus allowing us to distinguish between a gaseous planet and a terrestrial-type planet.

In some cases, when the observation may be made with a good signal-to-noise ratio, by using differential spectroscopy before and during the transit, it is possible to determine the composition (or at least the presence of certain elements) in the planet's atmosphere. It is also important to mention that the transit method has been used in the infrared, exploiting the fact that the planet is eclipsed when it passes behind the star (known as 'secondary transit'). Accurate knowledge of the ephemerides of the system allow us, by subtraction of the flux during the secondary transit (star alone) from that before the secondary transit (star + planet), to derive some spectral information about the object.

This technique has many advantages. Indeed, transit photometry is currently the most effective and sensitive method for detecting extrasolar planets, particularly from an observatory in space. No other method currently proposed can match either the volume of the search or its sensitivity. Transits can also provide scientists with a great deal of information about the planet that is not otherwise measurable. First and foremost, the "dip" in a star's luminosity during transit is directly proportional to the size of the planet. By monitoring the depth of the transit at different wavelengths, we can recreate the absorption spectrum and deduce the atmospheric composition of an exoplanet. Transit photometry searches can operate on a massive scale, monitoring several stars at the same time.

Although the effectiveness of this technique is proven, it also has some disadvantages. The planet must pass directly between its star and the Earth and this is not always the case. A transit lasts only a tiny fraction of the planet's total orbital period. It might take months or years for the planet to complete its orbit, but the transit would probably last only hours or days. As a result, even when astronomers observe a star with a transiting planet, they are extremely unlikely to observe a transit in progress. Experience with transit photometry has shown that the method tends to produce "false positives" - instances when a binary star is mistaken for a planet orbiting a star. For this reason, this technique gives us only planetary candidates and we have to verify with other methods if the candidate is actually a planet.

1.1.2.1. Limb Darkening

In reality, the luminosity of a star is not constant across the stellar disk. The photons received from the centre of the stellar disk come from deeper into the stellar atmosphere, having a higher temperature and thus appearing brighter at the associated wavelength, than those received from the edge of the disk. The name of the optical effect that makes the stellar disk appear brighter at its centre than at its edge is “limb darkening”.

Stellar atmosphere is divided in photosphere, chromosphere and corona. Photosphere is the layer in which the light seen from an observer originates. In the stellar interior, photons are diffused, re-absorbed and emitted. An emitted photon has a probability to escape from the stellar atmosphere dependent from the path, from the density of matter, and from the cross section.

For a given frequency ν , the optical depth τ_ν is defined as the integral of the density $n(z)$ of photon absorbers and emitters times the cross section σ_ν , across the path of the ray of light (Fig. 1.6)

$$\tau_\nu = \int_X^\infty n(z)\sigma_\nu dz \quad (1.20)$$

The probability of a photon to be absorbed or to be scattered in the photosphere is then $e^{-\tau_\nu}$. It follows that

$$I_{out} = I_0 e^{-\tau_\nu} \quad (1.21)$$

where I_{out} is the outgoing intensity of radiation and I_0 is the emergent intensity of radiation.

A distance equal to one optical depth is the thickness of the absorbing gas from which a fraction of $1/e$ photons can escape from the star and reach the observer. This is what defines the visible edge of a star, since it is at higher optical depths that the star becomes opaque. The radiation reaching us is closely approximated by the sum of all the emission along the entire line of sight, up to that point where the optical depth is unity.

For a black body emission, according to Stefan-Boltzmann law, the spectrally integrated intensity is proportional to the fourth power of the temperature. The effective temperature of stellar atmosphere decreases for an increasing distance from the center of the star. Since when we look at a star, at first approximation, the radiation comes from the point at which the optical depth is unity and that point

is deeper in when looking at the center, the temperature will be higher, and the intensity will be greater, than when we look at the limb.

The temperature in the atmosphere of a star does not always decrease with increasing height, and for certain spectral lines, the optical depth is unity in a region of increasing temperature. In this case we see the phenomenon of “limb brightening”. Further complication may arise considering stellar activity and a three-dimensional structure for the stellar atmosphere.

Using a realistic model of stellar limb darkening is of crucial importance when fitting transit light curves, as the shape of the limb darkening will influence the derived planet parameters. There are different limb darkening laws proposed in literature to model the variation of the intensity across the stellar disk. The most commonly used when fitting transiting exoplanets light curves are the linear, the quadratic, and the non-linear laws. However, in light curves with high precision photometry, the linear law is insufficient to correctly reproduce the intensity variation over the stellar disk. This intensity variation across the stellar disk is calculated from stellar

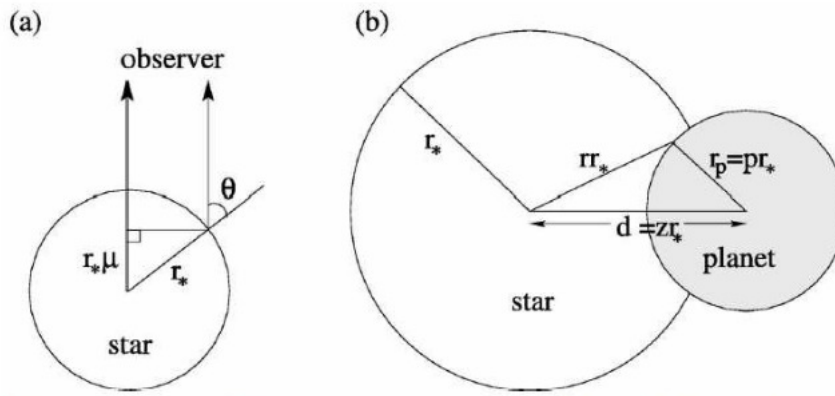


Fig. 1.6.: (a) Geometry of the limb darkening. R_* is the star radius, and θ is the angle between the observer and the normal to the star's surface, while $\mu = \cos \theta$. (b) Geometry of the transit seen by the observer. Image from Mandel and Agol (2002).

atmosphere models (e.g., PHOENIX as presented by Husser et al., 2013), where the emergent intensity with respect to the line of sight is known. This intensity is then passed through different instrumental filters, and fitted with different limb darkening laws to derive the associated limb darkening coefficients.

The limb darkening of main sequence stars is typically represented by functions of $\mu = \cos \theta$, where θ is the angle between the normal to the stellar surface and the observer's line of sight (see Fig. 1.6).

Claret (2000) proposed a non-linear limb darkening law that works well with different ranges of stellar models and wavelengths:

$$I(r) = \sum_{n=1}^4 c_n (1 - \mu^{\frac{n}{2}}) \quad (1.22)$$

where $\mu = \cos \theta = (1 - r^2)^{1/2}$, $0 \leq r \leq 1$ is the radial coordinate normalized on the stellar radius and $I(r)$ the radiation intensity in function of r or μ with $I(0) = 1$. The coefficients c_n depend on both the stellar parameters and wavelength of the light curve. The limb darkening causes in fact a more marked curvature with shorter wavelengths, while in the infrared this effect becomes almost negligible (Fig. 1.7). This effect can be well described with a quadratic function in μ (1.23):

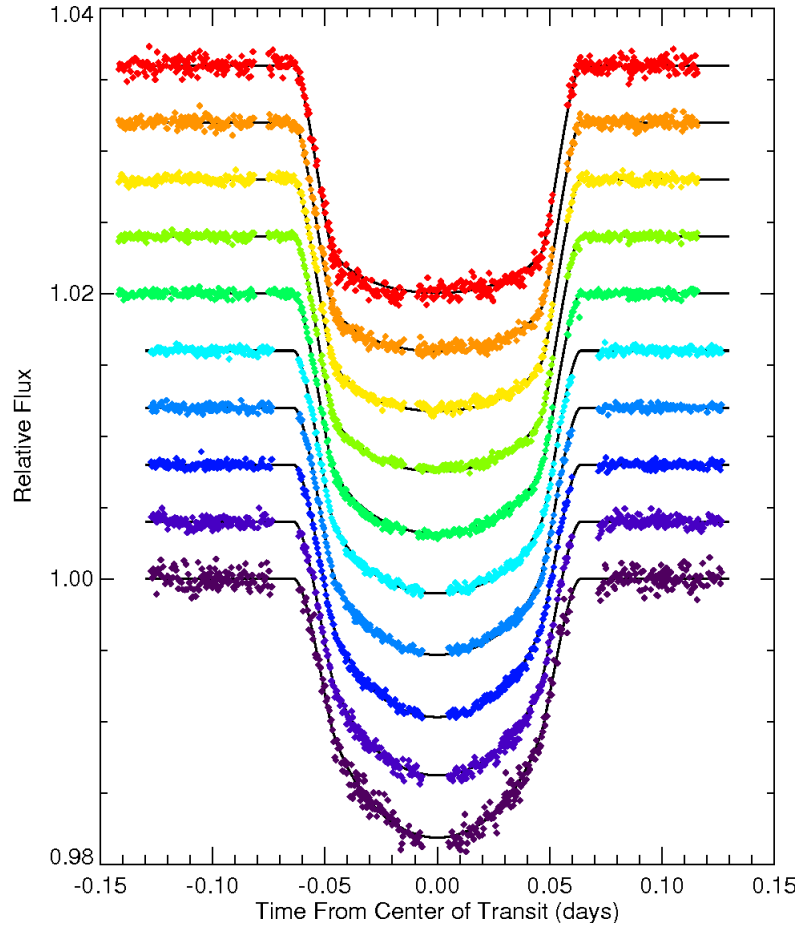


Fig. 1.7.: Normalized light curves (coloured) and theoretical models (lines) for ten different wavelengths from 3500 Å (top) to 9200 Å (bottom) of the transit of the planet HD 209458b (Knutson et al., 2007). The transit is clearly more flat at longer wavelengths (red light curve).

$$I(r) = 1 - \gamma_1(1 - \mu) - \gamma_2(1 - \mu)^2 \quad (1.23)$$

The non-linear law reduces to the quadratic law in the case $c_1 = c_3 = 0$, $c_2 = \gamma_1 + 2\gamma_2$, and $c_4 = -\gamma_2$, a very useful limit that permits to reduce both the number of free parameters and the time of calculation.

1.1.2.2. Rossiter-McLaughlin Effect

When a transiting planet eclipses part of the rotating stellar surface, it causes an anomalous Doppler shift of the stellar spectrum. Out of transit, the rotating star has a constant radial velocity, since the approaching (blue-shifted) and receding (red-shifted) portions of the surface contribute equally and cancel out. However, when the planet passes in front of the surface of the star, parts of the rotating star's surface are blocked and this causes an anomalous Doppler shift which changes the measured radial velocity in a predictable manner. This spectroscopic phenomenon is known as Rossiter-McLaughlin effect (RML) (Fig. 1.8). The shape of the perturbation

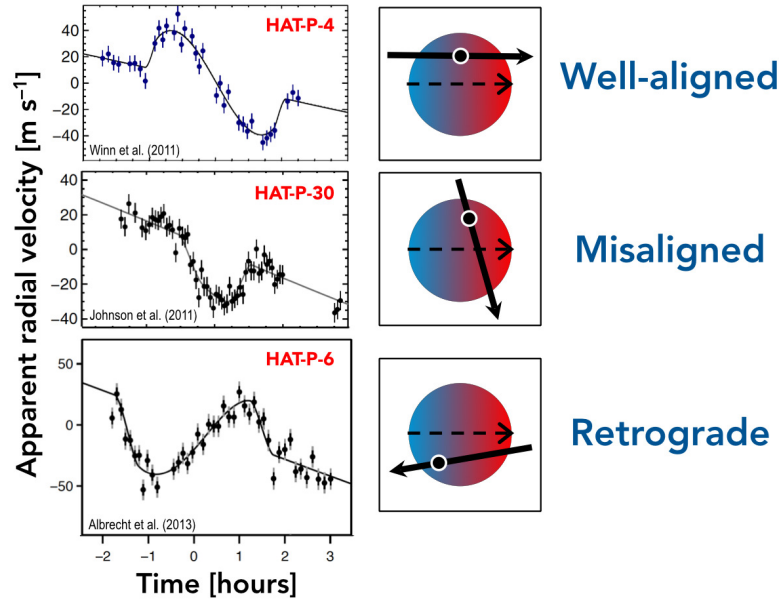


Fig. 1.8.: Three different possible trajectories of a transiting planet are shown, along with the corresponding RML waveform. The three planets are examples of spin-orbit alignment (HAT-P-4), of spin-orbit misalignment (HAT-P-30), and of retrograde motion (HAT-P-6). Credit: Winn et al. (2011)

mainly depends on the sky-projected angle, λ , between the stellar rotation axis and planetary orbital plane, whereas its amplitude is determined by the planet-to-star radii ratio and the projected rotational velocity ($V_{\star} \sin i_{\star}$) of the star.

The comparison between the amplitude of the stellar orbital velocity $A_{\star}$ and the RML effect A_{RV} is given by

$$\frac{A_{\star}}{A_{RV}} = \frac{V_{\star} R_p^2 P^{1/3} (M_p + M_{\star})^{2/3} \sin i_{\star} \sqrt{1 - e^2}}{(2\pi G)^{1/3} M_p (R_{\star}^2 - R_p^2) \sin i} \quad (1.24)$$

where $V_{\star}$ is the stellar surface velocity at the equator. Assuming $M_p^2 \ll M_{\star}^2$ and $R_p^2 \ll R_{\star}^2$, the equation becomes

$$\frac{A_{\star}}{A_{RV}} \approx \left(\frac{P}{2\pi G M_p} \right)^{1/3} \frac{V_{\star} \sin i_{\star} \sqrt{1 - e^2}}{\sin i} \left(\frac{\rho_{\star}}{\rho_p} \right)^{2/3} \quad (1.25)$$

Equation 1.25 shows that for transiting planets small in mass and/or with large orbits, the planet can create a larger amplitude RML effect than the radial velocity variations of its star. For an Earth-mass planet with a period of one year $A_{\star} A_{RV} \sim 3$ for $V_{\star} \sin i_{\star} = 5 \text{ km s}^{-1}$ (e.g., Gaudi and Winn, 2007). The RML effect confirmation appears feasible to confirm the planetary nature of Earth-like planets for at least some stars, not only because $A_{\star} > A_{RV}$ as mentioned above, but also because the RML velocity variation occurs over the time scale of the transit duration (~ 1 day), which is much shorter than the time scale of the orbital velocity variation (~ 1 yr). Crucial information on the mechanisms involved in the formation of planetary systems can be obtained by comparing the relative orientation of the host-star rotation axis, regarded as a relic of the angular momentum of the protostellar accretion disk, and the orbital axes of the planets, that may be largely affected by planet-planet interactions.

1.2 Secondary Discovery Methods

Techniques other than transits and RV have proven to be successful in the detection of exoplanets. In this Section, these discovery methods will be described in a general manner, highlighting their advantages and their weaknesses.

1.2.1 Timing Variation Methods

Unseen planets can make themselves known by the gravitational tugs they exert on other planets and stars, causing variations in the timing of predictable events like planetary transits, binary star eclipses, and natural pulses in radiation from stars. By observing timing variations, astronomers can infer the presence of a planet. This methods are best suited for finding large exoplanets and determining their mass,

as well as finding planets orbiting particular stars such as pulsars. Although this method is usually used to detect exoplanets, the presence of one of the planets in our own solar system was inferred through observation of timing variations. In the 1820s, astronomers noticed that Uranus moved slightly faster or slower in its orbit around the Sun than expected and several astronomers predicted that another, more distant planet was affecting its motion. In 1946, Neptune was discovered close to the predicted location.

As of January 2021, a total of 46 exoplanets were discovered by timing variation methods (7 using pulsar timing variation, 2 using pulsation timing variation, 21 using transit timing variation, and 16 using eclipse timing variation).

1.2.1.1. Pulsar Timing Variation

This method applies to stars showing high-periodicity phenomena, like pulsars. The precise radio pulse rates of pulsars and their stability allows to measure precisely variations in the position of the pulsar (Fig. 1.9). The variation in timing can occur due to a positional shift in the pulsar around the pulsar-planet barycentre. If the planet is in orbit around the pulsar, the two bodies will orbit around a mutual barycentre, each distance from the barycentre being determined directly by their mass-ratios, where $M_\star$ and $a_\star$ are the mass and the distance (semi- major axis) from the barycentre to the centre of the pulsar and M_p and a_p are the mass and the distance from the barycentre to the planet.

The presence of a planet orbiting the star is revealed by a variation in the arrival timing of the emitted waves. The movement of the star around the barycentre of the system slightly delays the signal if the pulsar is going in the opposite direction from the observer, and a small advance if the pulsar is getting closer.

For a planet in a circular orbit, the maximum amplitude of the variation is:

$$\tau_P = \sin i \left(\frac{M_P}{M_\star} \right) \left(\frac{a_P}{c} \right) \quad (1.26)$$

where i is the inclination of the planet's orbit ($i = 90$ degrees being edge-on) and c is the speed of light. The pulses will be 'on time' at phases $\varphi(t) = 90$ and 270 degrees, late by an amount τ_p at $\varphi(t) = 0$ degrees and early by an amount τ_p at $\varphi(t) = 180$ degrees orbital phase angle, where zero degrees phase is when the planet is closest to the observer. The sine function is not negative because the pulsar signals are being measured directly and the pulsar is at the opposite orbital phase from the planet. That said, the pulsar timing method can measure the projected planet-to-star mass

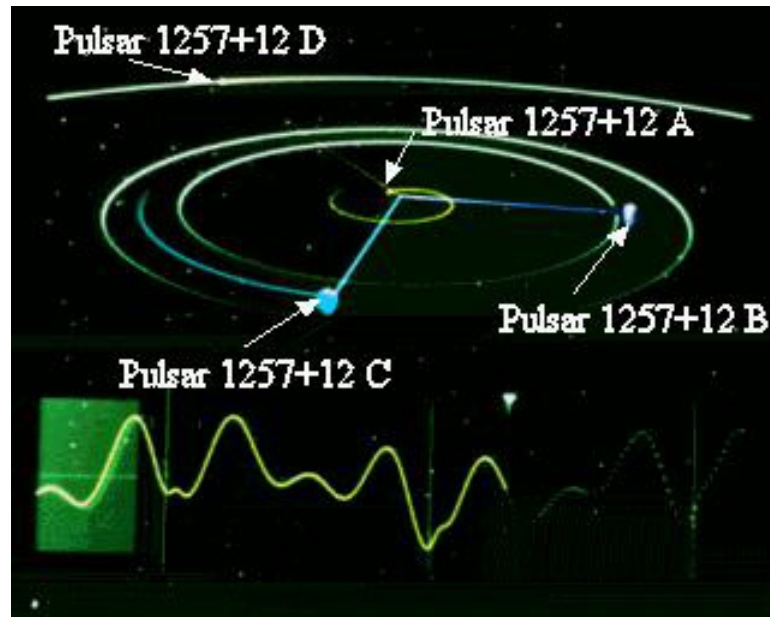


Fig. 1.9.: The motion of the pulsar around the centre of gravity makes the pulsation period to have slight anomalies, due to the finite speed of light

ratio, the true orbital period of the planet and its orbital eccentricity. This method is also capable of detecting mutual gravitational perturbation among the various members of a planetary system and can easily detect planets that are relatively far away from the pulsar.

The main limitation of this method is that pulsars are rare, so it is unlikely that a large number of planets will be found with this method. Also, this kind of discoveries do not attract a lot of attention: the electromagnetic environment of the pulsar is very hostile and so it leaves a little hope that these planets could host life as we know it.

However, the accuracy of this method allowed Wolszczan and Frail to discover the first exoplanet around the pulsar PSR 1257+12.

1.2.1.2. Pulsation Timing Variation

The stable oscillations of pulsating stars can serve as accurate timepieces, which may be monitored for the influence of exoplanets. Indeed, a companion gravitationally tugs the host star, causing periodic changes in pulsation arrival times.

This method is most sensitive to detecting substellar companions around particular classes of variable stars, because sufficiently stable oscillations are necessary and care must be taken to ensure that the changes in pulsation arrival times are not caused by intrinsic stellar variability. Only a handful of exoplanets have been claimed using the

pulsation timing method: the first one and the least-massive object claimed using the pulsation timing method was proposed by Silvotti et al. (2007) around the hot subdwarf V391 Pegasi. The data show evidence of the presence of a $m \sin i = 3.2 \pm 0.7$ M_{Jup} planet. Most secure is the object discovered by Murphy et al. (2016), likely near the deuterium-burning limit and that orbits near the habitable zone of an A star in the original Kepler mission. The star is the δ Scuti KIC 7917485 and the planet is an $m \sin i = 11.8^{+0.8}_{-0.6}$ M_{Jup} object in an 840^{+22}_{-20} day, slightly eccentric ($e = 0.15^{+0.13}_{-0.10}$) orbit.

1.2.1.3. Transit Timing Variation

Many extrasolar planets have been discovered by watching them transit their stars. Transiting planets in multi-planet systems have non-Keplerian orbits which can cause the times and durations of transits to vary.

Kepler-19 c was the first planet discovered by the transit timing variation method (Ballard et al., 2011). The transits of its sibling planet, Kepler-19b, showed as many as five minutes delay or anticipation than expected for an unperturbed planet. Therefore astronomers deduced the existence of the non-transiting companion Kepler-19 c. Followup radial-velocity measurements enabled astronomers to pin down its mass and orbit.

1.2.1.4. Eclipse Timing Variation

Eclipsing binary stars are pairs of stars that orbit each other and cross each other's faces as seen from Earth, causing the variation of the brightness of the whole system as one star blocks the other's light. As the stars in the binary are displaced back and forth by the planet, the times of the eclipse will vary. The periodicity of this offset may be the most reliable way to detect extrasolar planets around close binary systems. With this method, planets are more easily detectable if they are more massive, orbit relatively closely around the system, and if the stars have low masses.

Doyle et al. (2011) reported the detection of Kepler-16 b, the first planet definitely characterized via eclipsing binary timing variations. This object, whose nearly circular 229-day orbit surrounds a pair of low-mass stars (20% and 69% the mass of the Sun), is comparable to Saturn in mass ($M_b = 0.333 \pm 0.016$ M_{Jup}) and size ($R_b = 0.7538^{+0.0025}_{-0.0023}$ R_{Jup}).

1.2.2 Gravitational Microlensing

One of the most surprising aspects of Einstein's relativity theory is the phenomenon of the gravitational lenses (Einstein, 1936). In his theory, Einstein introduced the energy/matter equivalence, with the consequence that the photon is subject to gravitation. So a photon that passes at a distance r from an object of a point-like mass M , undergoes a deflection α relative to its direction of propagation. The deflection is given by:

$$\alpha = \frac{4GM}{c^2 r} = \frac{2R_S}{r} \quad (1.27)$$

where R_S is the Schwarzschild radius of the gravitational lens caused by the point mass. The gravitational lensing was primarily observed in galaxies, but it is possible to use it also in exoplanetary astronomy. The light from a background source is bent by the gravitational field of a foreground lensing star to create distorted, multiple and/or brightened images. When the mass of the deflecting object is low and α is

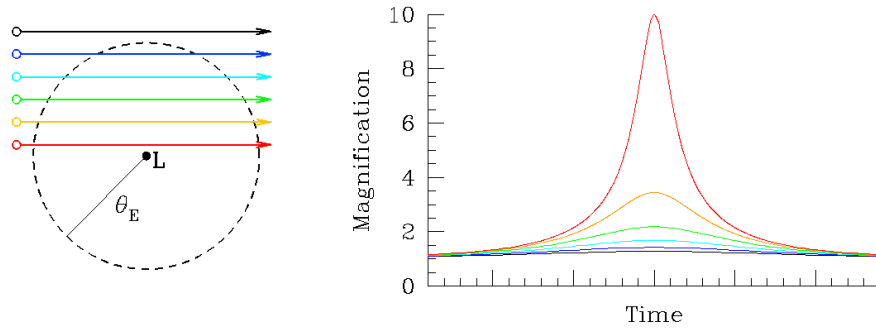


Fig. 1.10.: (left): Possible source trajectories are shown in different colours with respect to a single microlens L with an Einstein radius θ_E . (right): Light curves of the background source star are shown, colour-coded to match their corresponding trajectories at left.

less than the angular size of the observing instrument's diffraction disk, the situation is described as a 'microlens'. The combined light of all images is instead observed as a single amplified image of the source observed.

Gravitational amplification is given by:

$$A = \frac{u^2 + 2}{u\sqrt{u^2 + 4}} \quad (1.28)$$

where $u = \theta_S/\theta_E$, with θ_S the angular distance between the source and the deflector, and θ_E the Einstein radius, which is defined as:

$$\theta_E = \sqrt{\frac{4GM}{c^2} \frac{d_{LS}}{d_L d_S}} \quad (1.29)$$

where G is the gravitational constant, M the mass of the lens, c the speed of light, d_L the distance between the observer and the lens, d_S the distance between the observer and the source and d_{LS} the distance between the source and the lens.

The brightness of the image is a function of the projected separation of the source, lens on the observer's sky, and thus can change as the source, lens and observer relatively move relative to each other. The time variability of the combined image – an apparent change in the source brightness as a function of time recorded as a microlensing light curve – is the observational signature of microlensing. In the case of a simple lens and, if relative motions are rectilinear, the light curve of the background source is simple, smooth and symmetric (Fig. 1.10). The background star appears to brighten and then dim as the projected separation between the source and lens first decreases and then increases.

This method has been used since 1995 to try to detect dark matter in the Milky Way. The theory to be verified is that dark matter consists of massive, compact, and non-luminous objects, whose overall masses could explain the difference between the deduced mass from the dynamics of the Galaxy and the mass that is directly observable.

For planet hunters, this technique became important for the search of exoplanets orbiting faint stars and brown dwarfs, which would be difficult to detect by any means other than microlensing.

If the lensing stars are multiple, as in the case of a binary star or a star with planets, the magnification pattern experienced by a background source is no longer circularly symmetric. In this case, the shape and maximum amplitude of the light curve depends on the relative path the background source takes through the lens magnification pattern. The resulting light curve can show large variations in shape over short periods of time if the background star passes near what is known as a caustic in the lensing pattern (Mao and Paczynski, 1991) (Fig. 1.11).

The key parameters sought from the microlensing light curves show the presence of a planet are:

- The mass ratio between the planet and its parent star, $q = M_p/M_S$.

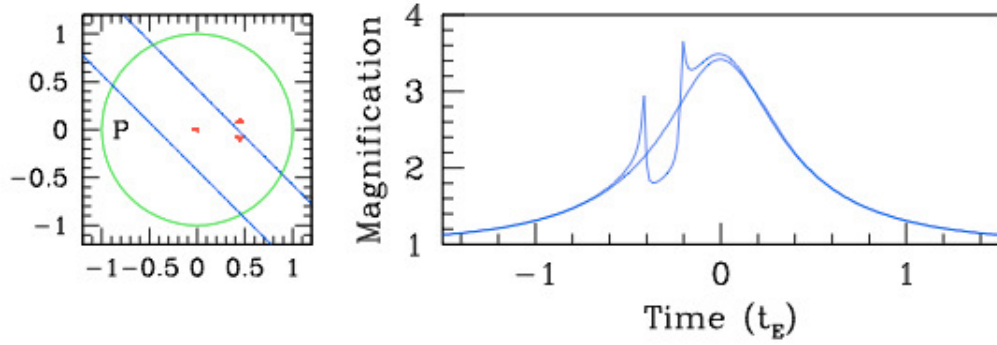


Fig. 1.11.: Microlensing exoplanets can cause sharp deviations in the otherwise smooth light curve of a background star during a microlensing event, but only if the path of the background star passes near one of the caustics (shown as red zones) caused by the combined gravitational potential of the planet and its host lensing star. Two possible background star trajectories are shown at left, and the resulting light curves are displayed on the right. The green circle is the Einstein ring, and the position of the planet is marked with a P. The Einstein time depends on the relative proper motion μ of the lens with respect to the source through $t_E = \theta_E / \mu$, and thus is different for different microlensing events.

- The angular separation between the planet and the star on the sky at the time of the lensing event, $d = \theta_{S,P} / \theta_E$, in units of the Einstein ring radius.

Note that the denominators depend on the mass of the lensing star, while the Einstein radius depends on the relative distance of the lensing star along the sight line of the observer. The quantity q indicates how massive the planet is compared to its host star. If the size of θ_E can be measured (which is possible for planetary microlensing events), then d places a lower limit on the size of the orbit.

This technique has many advantages but also many limits. The advantages include:

- More sensitive than other techniques to detect small-mass planets;
- More sensitive to planets in our Galaxy that have orbits of a few astronomical units.
- It is the only method capable of detecting planets in other galaxies.
- Capable of detecting multiple planets in a single light curve.

The disadvantages of the microlensing technique include:

- Millions of stars must be monitored to find the few that are microlensing at any given time.

- Planetary deviations in light curve do not last for long and could be missed due to inopportune timing.
- Substantial probability that any planet will not be detected in lens system, even if present.
- Deviations in microlensing light curves due to planets will not repeat (as they are due to a chance alignment).
- Planetary parameters (such as mass, orbit size, etc.) depend on the properties of the host star, which are typically unknown.

In conclusion, this method requires an intensive use of telescope time, so it is unsuitable for continued detailed studies of individual exoplanets. However, this method real strength is its sensitivity to planets distant from their host stars when compared to the other methods (see Fig. 1.12). Therefore, microlensing is a very

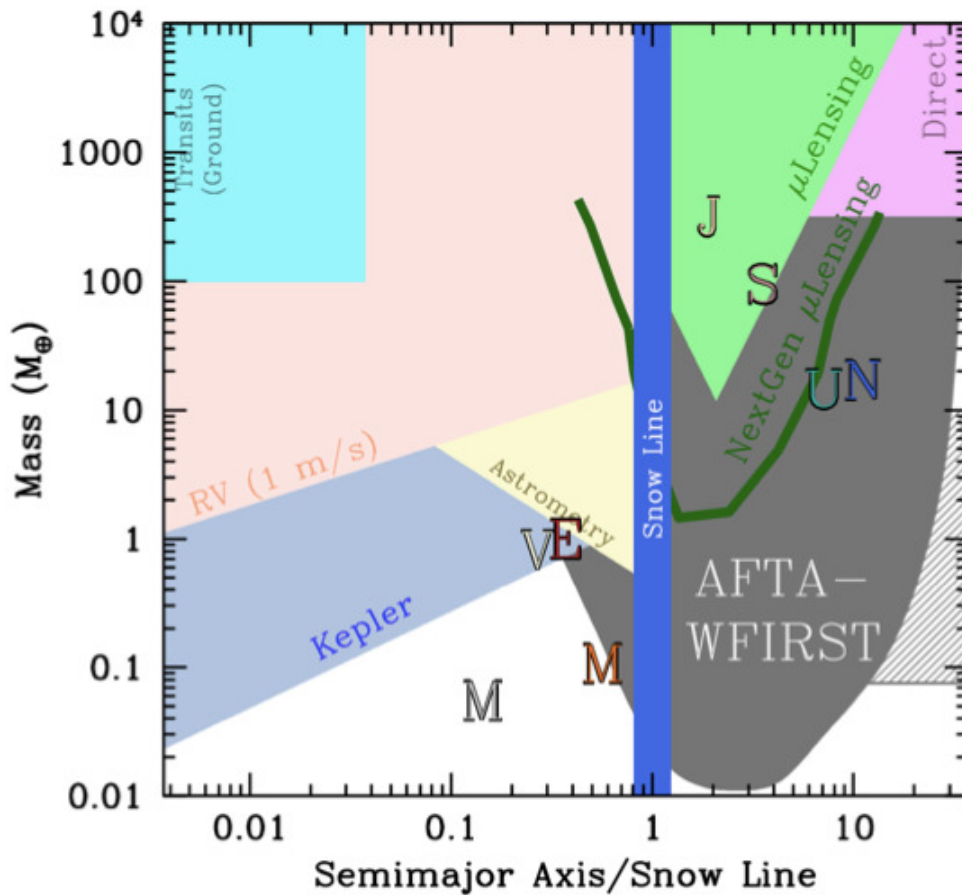


Fig. 1.12.: Sensitivity of microlensing compared to other techniques. Figure courtesy B. Scott Gaudi and Matthew Penny. Source Fischer et al. (2014)

powerful instrument to complete the exoplanet census begun by Kepler and gain a comprehensive understanding of the architecture of planetary systems, needed to understand planet formation and habitability.

1.2.3 Astrometry

As the planet or planets move around the centre of mass of the star-planet system, the central star also describes an orbit, the complexity of which depends on the number of planets in the system. Figure 1.13 shows the complex motion of the Sun due to the planets in the Solar System. In the case of a system with a single planet, the motion of a star is an ellipse. The general equation for such orbits, using polar coordinates having their origin at the focus, is:

$$r(\gamma) = \frac{(1 - e^2)}{1 + e \cos \gamma} \quad (1.30)$$

where a is the semi-major axis, e the eccentricity and γ the angular position of the object relatively to an origin given by the orbit's periastron.

The motion, projected onto the plane of the sky, is deduced from the preceding expression and assuming that the star's orbit is circular. The maximum value of the amplitude of the motion may be written as:

$$\delta\theta = \frac{M_p a_p}{M_\star D} \quad (1.31)$$

where M_p and $M_\star$ are the masses of the planet and the star, respectively; a_p is the semi-major axis of the planet's orbit, and D is the distance of the exoplanetary system from Earth. The equation clearly shows that the astrometric method is more sensitive, that is the amplitude of the motion of the star is the greater, if the planet is massive and/or located at a great distance from the host star.

However, the greater the distance of the planet from the star, the longer the planet's orbital period. This means that the time required to detect the planet increases with the planet's distance from the star. Nevertheless this method remains one of the most sensitive to low-mass objects, orbiting far from their star. In the case where the system is multiple, the path of the star rapidly becomes complex, and the accuracy of the reconstruction becomes limited by the resolution of the measurements.

This method is also useful in the follow up observations of planets found with the radial velocity method, because it allows to measure the angle of inclination and then the exact mass of the planet (Roell et al., 2008; Benedict et al., 2006). The

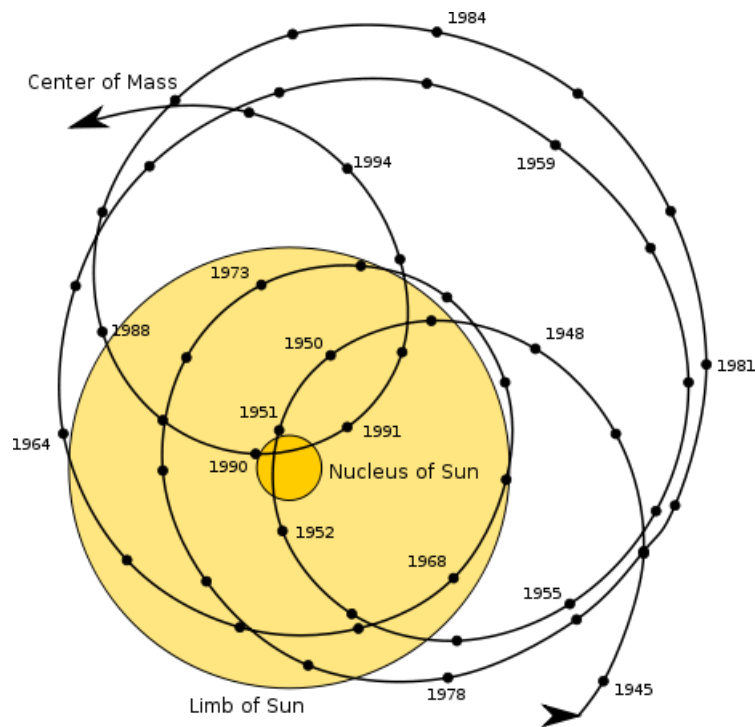


Fig. 1.13.: Motion of the Solar System's barycentre as a function of time (in years) on the plane of the sky as it would appear from a location 10 parsecs away and perpendicular to the plane of the ecliptic. This movement is mainly dominated by the giant planets (Jupiter, Saturn, Uranus, and Neptune).

cartoon in Fig. 1.14 shows how a telescope catches the motion of the star due to the presence of a planet.

A new ESA mission designed for astrometry started on December 2013. The Gaia mission aims to monitor each of its target stars about 70 times over a period of five years and create a precise three-dimensional map of astronomical objects throughout the Milky Way. It will map their positions, distances, motions and changes in brightness. Gaia is expected to find new extrasolar planets thanks to its very precise astrometry, reaching an accuracy of 24 microarcseconds for targets brighter than magnitude 15.

In reality, the spacecraft has not reached yet the desired results due to calibration problems, but astrometry has a brilliant future and we can expect new discoveries in the years to come.

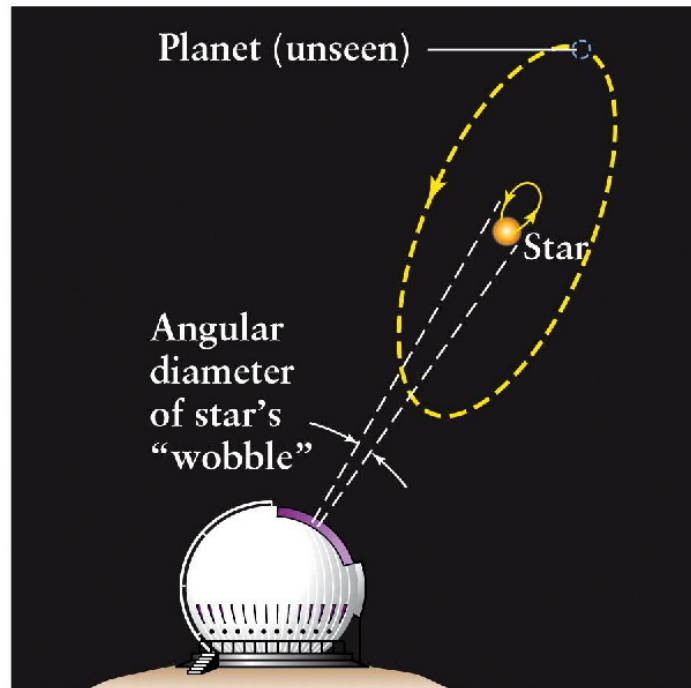


Fig. 1.14.: This figure explains how astrometry catches the presence of an exoplanet.

1.2.4 Direct Imaging

The direct observation of an exoplanet - in the sense of being able to separate physically the photons coming from the planet from those coming from the central star, enough to obtain an image of the two objects - is a problem that is as simple to state as it is difficult to achieve in practice (Fig. 1.15).

I may summarize it by three critical points that strongly influence the detection methods:

- The contrast between the star and the planet.
- The angular distance between the two objects.
- The atmosphere of Earth and of the exoplanet.

The aim of direct detection is to be able to make a spectroscopic analysis and to deduce the planet's luminosity, temperature, atmosphere and orbit. The choice of a spectral region for direct observation is crucial and involves a compromise between the planet-to-star contrast (typically between 10^4 and 10^{10} , depending on the nature of the companion and the spectral region chosen), and the angular resolution of the

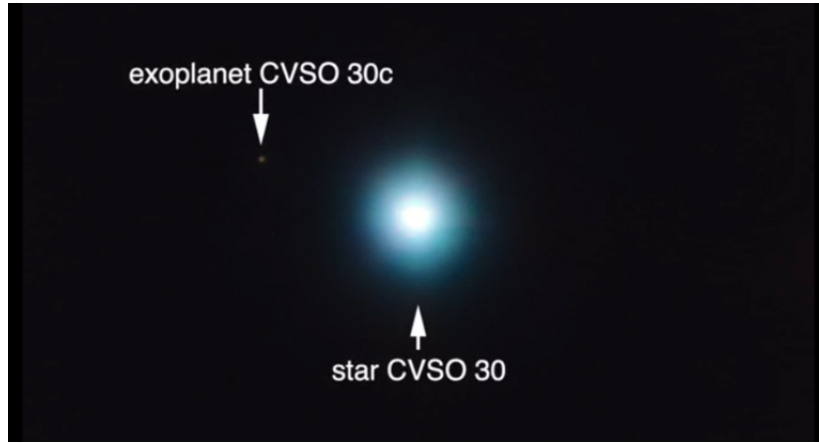


Fig. 1.15: Planet ‘c’ of the CVSO-30 system, imaged by the European Southern Observatorys Very Large Telescope (VLT) atop Paranal.

instrument, which primarily depends on the size of the collector.

Resolving power is the ability of an imaging device to separate (i.e. to see as distinct) points of an object that are located at a small angular distance (Fig. 1.16). The imaging system’s resolution can be limited either by aberration or by diffraction causing blurring of the image. These two phenomena have different origins and are unrelated. Aberrations can be explained by geometrical optics and can in principle be solved by increasing the optical quality – and subsequently the cost – of the system. Diffraction sets the limiting angular resolution. The image of a point at infinity through a telescope is not a point but a disc, with form and size dependent on the shape and size of the telescope’s aperture. The interplay between diffraction and aberration can be characterised by the point spread function (PSF). The narrower the aperture of a lens the more likely the PSF is dominated by diffraction. In that case, the angular resolution of an optical system can be estimated by the Rayleigh criterion:

Two point sources are regarded as just resolved when the principal diffraction maximum of one image coincides with the first minimum of the other. If the distance is greater, the two points are well resolved and if it is smaller, they are regarded as not resolved. Rayleigh defended this criteria on sources of equal strength.

If one considers diffraction through a circular aperture, this translates into:

$$\theta = 1.22 \frac{\lambda}{D} \quad (1.32)$$

where θ is the angle of the first minimum, λ is the observational wavelength and D is the diameter of the telescope’s primary mirror. To image an exoplanetary system,

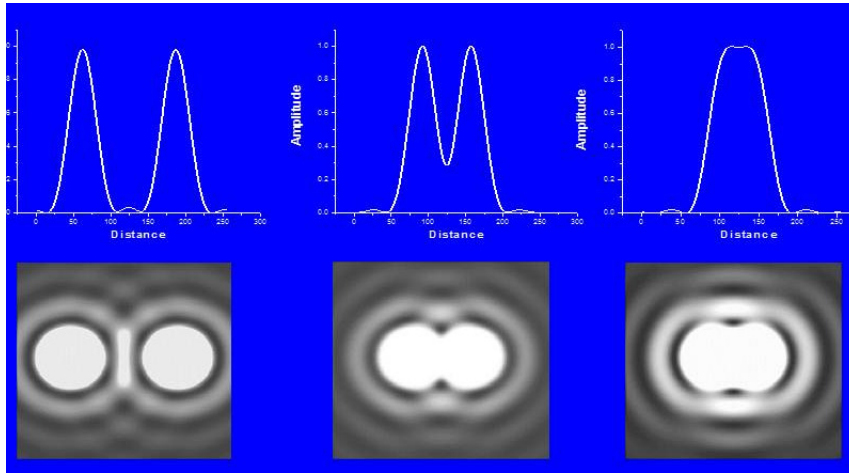


Fig. 1.16: Airy diffraction patterns generated by light from two points passing through a circular aperture, such as the pupil of the eye. Points far apart (left) or meeting the Rayleigh criterion (middle) can be distinguished. Points closer than the Rayleigh criterion (right) are difficult to distinguish.

taking account of its spatial size, the compromise finally comes down to a choice between two domains:

- The visible and near infrared, where a telescope a few meters in diameter spatially resolves the star and planet pair. The difficulty lies in overcoming the contrast, which is $10^9 - 10^{10}$ for a terrestrial-type planet.
- The thermal infrared (around $10\ \mu\text{m}$). In this band, the contrast is optimal (10^7 for a terrestrial-type planet), but we have to resort to interferometry to obtain the angular resolution of the star and planet pair.

Nowadays, the most powerful technique is to obscure in some way the light from the star using coronagraphic techniques. How does a coronagraph work?

A brief description of how a coronagraph operates may be made using Fourier optics and image formation theories. From the point of view of the theory of the formation of images, the principle behind coronagraph may be described as it follows:

1. At the entry pupil plane: the infinite (i.e. plane) wavefront is sampled by the pupil.
2. At the primary image plane (the focus of the main mirror): the image of a single point at an infinite distance (the Point Spread Function, PSF) is the square of the modulus of the pupil's Fourier transform and may be multiplied by the mask's transmission ($1 - \Pi$, where Π is the aperture function), corresponding to a mask with an occulting centre. In this image plane the result is:

$$image = PSF - PSF \times \Pi \quad (1.33)$$

3. At the secondary pupil plane: the new pupil is once again the Fourier transform of the primary image. In other words, the final transmission of a coronagraph is thus 0 on the optical axis, and there remains only an annulus (of scattered light), which may be written as:

$$pupil = \Pi - \Pi \otimes Airy \quad (1.34)$$

where the symbol $\otimes$ represents the second magnitude convolution product and Airy is the Airy function.

There are different kind of coronagraphs, but they all work through these steps. Furthermore, coronagraphs have requisites in common: the necessity for the stellar source to be perfectly centred on the centre of the mask, and for the stellar image to be as symmetrical as possible. Any deviation from symmetry results in a stellar residue, which may mask the image of the companion that is being sought.

For this reason, all current coronagraphic systems operating from ground take advantage of advantage of adaptive optics² (Fig. 1.17) in order to minimize the effect of the atmospheric turbulence. The effect of the images is called seeing and it refers to the blurring and twinkling of astronomical objects such as stars induced by turbulent mixing in the Earth's atmosphere. The atmospheric mixing causes quantitatively similar variations in the refractive index throughout the visible and near infrared wavebands and dealing with the astronomical seeing conditions on a given night at a given location allows us describe how much the Earth's atmosphere perturbs the images of stars as seen through a telescope.

Astronomical seeing has several effects:

1. It causes the images of point sources, which in the absence of atmospheric turbulence would be steady Airy patterns produced by diffraction, to break up into speckle patterns, which change very rapidly with time.
2. Long exposure images of these changing speckle patterns result in a blurred image of the point source, called a seeing disc.

²Adaptive optics is a technology used to improve the performance of optical systems by reducing the effect of wavefront distortions: it aims at correcting the deformations of an incoming wavefront by deforming a mirror in order to compensate for the distortion. Adaptive optics works by measuring the distortions in a wavefront and compensating for them with a device that corrects those errors such as a deformable mirror.

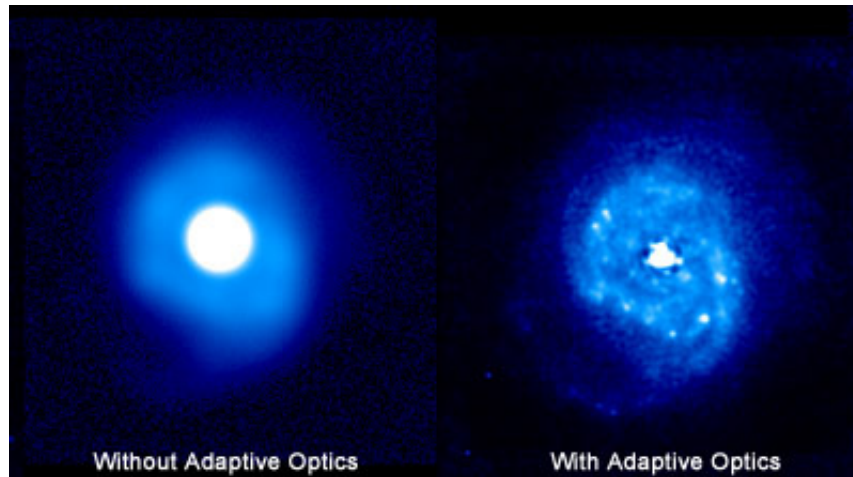


Fig. 1.17.: Difference between an image without adaptive optics(left) and with adaptive optics (right). Credit: CanadaFranceHawaii Telescope (CFHT)

3. The brightness of stars appears to fluctuate in a process known as scintillation or twinkling.
4. Atmospheric seeing causes the fringes in an astronomical interferometer to move rapidly.

With today’s technology, direct imaging is possible only in rare and unusual situations, but on the occasions when it is feasible, it can provide scientists with valuable information about the planet. This technique works best for “bright” planets that orbit at a great distance from their stars, and for planetary systems that are positioned “face on” when observed from Earth.

The Spectro-Polarimetric High-contrast Exoplanet REsearch (SPHERE) instrument installed on Unit Telescope 3 of the Very Large Telescope (VLT) has proven its effectiveness as a powerful tool to find and characterize planets. In the next future, two other instruments will further improve our capability of studying planets outside our solar system in greater detail. The two SHARK (System for coronagraphy with High order Adaptive optics from R to K band) instruments at Large Binocular Telescope (LBT) will enable astronomers to obtain direct images of exoplanets, including very faint ones, by more effectively blocking the otherwise overpowering light from their host stars and by taking full advantage of the outstanding adaptive optics system mounted on the LBT.

1.3 Main Characteristics of Exoplanets

Over the centuries, astronomers gradually become aware of many properties of the Solar System. Eight planets orbit around the Sun in nearly circular and aligned orbits, with the four smaller planets ($R_p = 0.4 - 1.0R_\oplus$) interior to the four larger planets ($3.9 - 11.2R_\oplus$). The Sun's rotational angular momentum is much smaller than the orbital angular momentum of the planets and its equator is tilted by 6.0 degrees relative to the invariable plane.

This regularities have long been recognized as important clues about the formation of the Solar System. Since the first exoplanets discoveries, astronomers tried to recognize the same type of information for other planetary systems. They found out that while some exoplanetary systems have properties that are familiar with those of the Solar System, many have different characteristics. This diversity echoes the Copernican principle that the Earth is not the center of the universe and the Solar System does not provide a universal template for planetary system architectures. Measurements of the properties of a large number of planetary systems can probe the mechanisms of planet formation and place our Solar System in context. These surveys can answer questions such as, what are common planet sizes and architectures and how did such planetary systems form?

1.3.1 Occurrence

There are no physical principles that tell us whether planets should be rare or common. Prior to the discovery of exoplanets, there was ample room for speculation. According to “monistic” planet formation theories, planet and star formation are strictly related and planets should be ubiquitous. In contrast, in “dualistic” theories planets arise from events that are completely distinct from star formation and in many such theories the events were extremely unlikely.

Today, over 4000 extrasolar planets have been discovered and the results of planet surveys show that stars with planets are very numerous. For most of these planets we could determine only one of their fundamental parameters directly: radius or mass. In those cases where planets have been observed by both the transit and radial velocity methods, their mass, radius, and thus mean density have been measured. Even though the precise frequency of planets in the Milky Way is matter of debate, demographics studies show that planets are very common around solar-type stars (FGK and M dwarfs - see e.g. Udry and Santos, 2007a; Mayor et al., 2011a; Howard et al., 2012a; Bonfils et al., 2013). Giant planets with periods ranging a few years are found around $\approx 10\%$ of Sun-like stars, while hot Jupiters, despite their importance

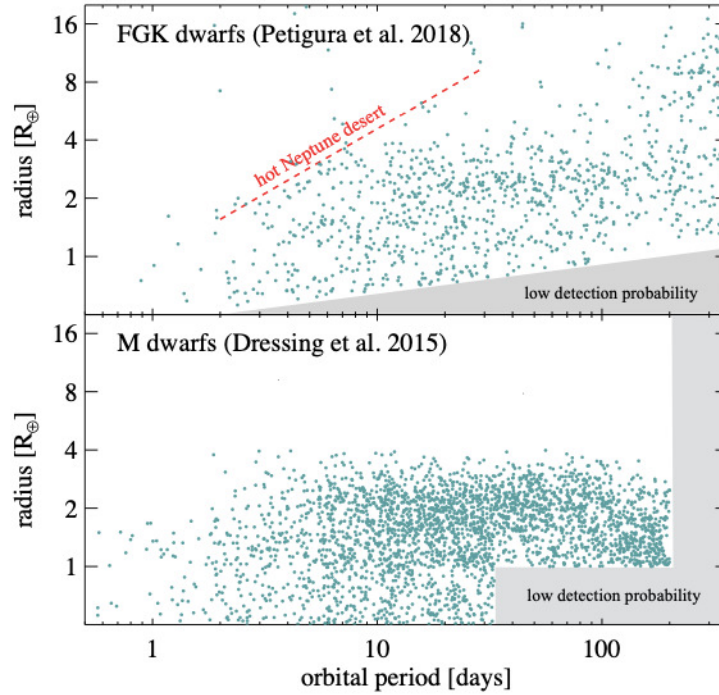


Fig. 1.18: Planet occurrence around FGK dwarfs (top) and M dwarfs (bottom) based on Kepler data. The blue dots represent a random sample of planets around 103 stars, drawn from the occurrence rate densities of Petigura et al. (2018) and Dressing and Charbonneau (2015). Compared to FGK stars, the M stars have a higher occurrence of small planets and a lower occurrence of giant planets. Note that there seems to be a lack of Neptune-like planets in close-in orbits, an effect probably caused by atmospheric erosion. Image from Winn (2018).

in radial velocity and transit surveys, have an occurrence rate estimated to be lower and around 0.5 – 1% for periods between 1 and 10 days (e.g., Mayor et al., 2011a; Santerne et al., 2016). Smaller planets are even more common. About half of Sun-like stars have at least one planet with an orbital period shorter than 100 days and a size in between those of Earth and Neptune (e.g., Howard et al., 2012b).

Figure 1.18 provides an overview of the exoplanet occurrence around FGK dwarfs (top panel) and M dwarfs (bottom panel) based on Kepler data (Winn, 2018). The previous Sections presented the sensitivity of the detection methods to some characteristics of the planets. It is therefore important to note that the accurate measurement of occurrence rates requires large surveys and a good understanding of the selection effects that favor the discovery of certain types of planets. Jupiter-sized planets are well represented out to several AU. Detections beyond ~ 0.1 AU are dominated by the radial velocity technique which provides lower mass limits. Masses and radii are known mainly for close-in planets, where data from both transits and radial velocity are available.

Transit detections beyond about 0.1 AU are very difficult from the ground due to the limited duty cycle of observations caused by the Earth's rotation. The known transits at intermediate orbital separations result from CoRoT and Kepler/K2 missions, showing that transit detections of planets at larger orbital separations are feasible from space. However, Kepler did not provide us with planet bulk parameters for the vast majority of its discoveries since most of its targets are too faint to allow for a direct measurement of terrestrial planet masses. The range of terrestrial planets as found in our Solar System, with masses from Earth-down to Mercury-sized objects beyond 0.3 AU, is still basically unexplored today.

Recent studies are focusing on the existence of Earth-like planets. How common

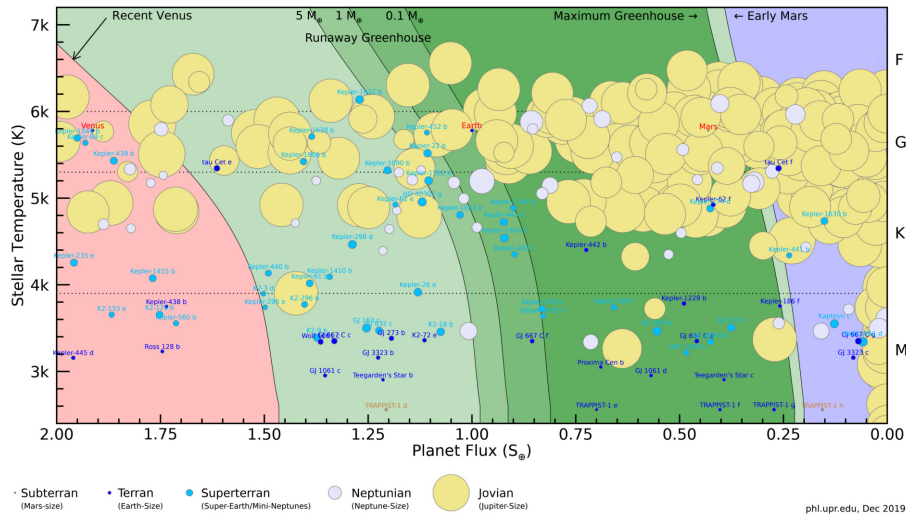


Fig. 1.19: Planets near the habitable zone (darker green shade is the conservative habitable zone and the lighter green shade is the optimistic habitable zone). Only those planets less than $10 M_{\oplus}$ or $2.5 R_{\oplus}$ are labeled. The different limits of the habitable zone are described in Kopparapu et al. (2014). Size of the circles corresponds to the radius of the planets (estimated from a mass-radius relationship when not available). Image from **PHL @ UPR Arecibo**.

are they?

The Kepler mission, despite being barely sensitive to such planets, provided excellent data for measuring the occurrence rate of Earth-sized planets orbiting Sun-like stars within the “habitable zone”, the range of distances within which a rocky planet could plausibly host oceans of liquid water. The percentage occurrence rate of Earth-like planets $\eta_{\oplus}$ around main sequence stars has proven to be difficult to measure and results strongly depend on the assumptions made, but all relate to the following expression:

$$\eta_{\oplus} = \int_{R_{min}}^{R_{max}} \int_{S_{min}}^{S_{max}} \frac{\partial^2 n}{\partial \log S \partial \log R} d \log S d \log R \quad (1.35)$$

where S is the bolometric flux the planet receives from the star and the integration limits are chosen to select planets likely to have a solid surface with a temperature and pressure allowing for liquid water (e.g., Kasting et al., 2014).

Figure 1.19 shows the current status of Super-Earth planet detections in comparison to the position of the HZ. Most super-Earths have been found at orbital distances to the star closer than the HZ. Detections in the HZ have been made by radial velocity or transit measurements. However, only a small number of super-Earths have both mass and radius determined, and most of these do not lie in the HZ. The super-Earth population has a number of intriguing characteristics that constrain planet formation models.

From the basic picture that emerges from the surveys, it is possible to see that nature seems to distinguish between giant planets and smaller planets. Giant planets are less abundant than smaller planets within a short period range and are also associated with a higher heavy-element abundance in the host star's photosphere and a broader eccentricity distribution than smaller planets.

Smaller planets ($1-4 R_{\oplus}$) with $P \leq 1$ yr are found around about half of Sun-like stars, often in closely-spaced multiplanet systems (Dressing and Charbonneau, 2015). Analyses have shown that the smaller planets tend to have high densities and the larger ones have low densities, which has been interpreted as a transition between rocky 'super-Earths' and gas-rich 'mini-Neptunes' with a transition size or mass of roughly $1.5-2 R_{\oplus}$ or $\sim 3 - 5 M_{\oplus}$ (see Chapter 2 for further details).

1.3.2 Composition

While mass and size distributions provide valuable information about the relative occurrence of planets of different types, a more challenging task is to connect the two. Knowing the mass of a planet does not specify its size, and vice versa.

Planets larger than $\sim 100 M_{\oplus}$ show a variation in size by a factor ~ 2 , showing then a small size dispersion (e.g., Howard, 2013). The models for the bulk composition of these planets are Jupiter and Saturn, essentially giant spheres of hydrogen and helium with smaller contributions from heavier elements and complex molecules. Some gas giants, probably not all of them, have heavy-element cores at their centers and just above the core there is a region in which chemical composition is presumably well-mixed, a deep envelope extending almost the entire radius of the planet in which opacities are high enough that heat must be transported via convection (Fortney and Nettelmann, 2010). A radiative-convective boundary separates the

deep envelope and the atmosphere, the thin outer region that consists mostly of molecular hydrogen.

Planets less massive than $\sim 30 M_{\oplus}$ vary in radius by a factor 4 - 5 (Howard, 2013). Masses and radii of intermediate planets lead to various interpretations about their possible composition. Possible models for these type of planets are Uranus and Neptune. Structure models find that these planets still have a thick H/He envelope, but the light-element envelope does not comprise the majority of the planet's mass which instead consists in a deep fluid ionic sea probably consisting predominantly of water, and also containing ammonia and methane. The heaviest material, such as rocks and iron, should be concentrated in the inner core (for a review on intermediate-mass planets see Helled and Bodenheimer, 2014).

The smaller planets are expected to be terrestrial planets, objects similar to Mars, Venus, and Mercury that are composed predominantly of elements such as Si, Mg, Fe, O, and, perhaps in some cases, C (Sotin et al., 2007). The Earth is also a model for these exoplanets, but disentangling whether they are more similar to Venus or our planet is very difficult. Venus and Earth have about the same mass and radius, but their present-day conditions differ so much that it is unlikely that their distance from the Sun could have such a strong influence on their evolution (1.20). Among the major differences between Venus and Earth is the lack of current plate tectonics on Venus (e.g., Basilevsky and Head, 2002): this geological phenomenon plays an important role on Earth, providing a very efficient way of cooling the Earth's interior and an exchange mechanism between the interior, the surface, and the atmosphere. A very useful tool used to infer the composition of an exoplanet is the mass-radius

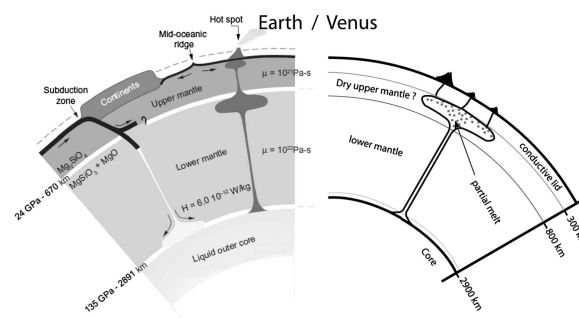


Fig. 1.20.: Schematic representation of the interior structure and dynamics of the Earth (Left) and Venus (Right). On Earth, hot matter from the mantle rises, causing plates to form and diverge. Where plates converge, a cooled plate is dragged under the neighboring plate, sinks, warms and rises again. On Venus, in contrast, currents are more vigorous, preventing thick crust from forming and leading to violent transformations of the thin crusts that does form. The surface crust breaks up into crumples and blobs of hot lava bubble up to form large landmasses, mountains, and volcanic deposits. Image from Spiegel et al. (2014).

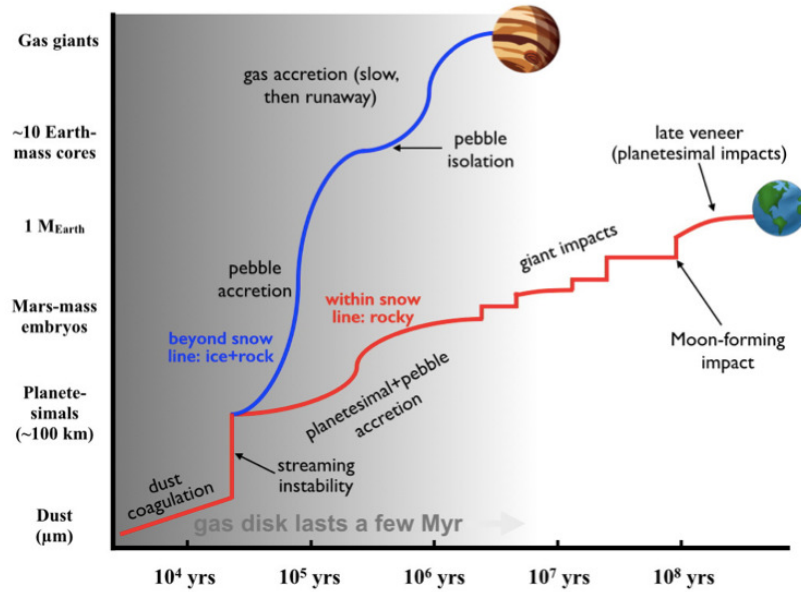


Fig. 1.21.: Schematic view of some of the processes involved in forming Jupiter and Earth. This diagram is designed to present a broad view of the relevant mechanisms, but not all of them. It is however a useful method to illustrate how divergent formation pathways can contribute to planetary diversity. Image from Meech and Raymond (2019).

diagram (discussed more in detail in Chapter 2), a plot that shows the relation between the mass and radius of planets and connects the data with theoretical mass-radius curves that set the limits for interior composition of the planet.

1.3.3 Planet Formation

An understanding of how planets form is essential in understanding and interpreting the considerable range of observed planetary systems, including close-in small/low-mass planets, giant exoplanets, and the Solar System's planets.

The diversity of planetary systems can actually be explained by different combinations of processes drawn from a common set of physical mechanisms. Figure 1.21 shows a scheme of our current vision for the growth of Earth and Jupiter.

As the catalog of known exoplanets grows, the constraints we already had from our system's orbital architecture are constantly being improved. The main observational constraints coming from protoplanetary disks for planet formation models are given by the disks lifetime, their masses, and their structure and evolution. Other valuable information are given by the occurrence and orbital distribution of the different types of planets.

The next Paragraph briefly presents the key processes that affect the disk's structure, planetesimals and planet formation and resumes the main models on the origin of the different observed structures of planetary systems.

1.3.3.1. Protoplanetary Disks and Dust Growth

The first stage of planet formation takes place within protoplanetary disks, gas-dominated disks around young stars. The simplest model of a protoplanetary disk is the viscous-disk model, a donut of gas and dust in rotation around the central star in which different rings rotate with different angular velocities, depending on their distance from the star. The inner ring exerts friction on the outer one and vice versa. The main limitation of this model is in the understanding of the origin of the disk's viscosity: turbulence could be the main source of viscosity. However, observations show stellar accretion rates too high to be explained by turbulent viscosity and for this reason an alternative model, dominated by the existence of winds, was promoted. The winds are consequence of non-ideal magneto-hydrodynamics (MHD) effects and could be the main process removing angular momentum from the disk, thus causing gas to accrete onto the central star. The actual strength of the turbulence and the associated viscosity in the inner disk is still unknown, but it is a key parameter for planetesimal growth (for further readings the reader can refer to Armitage, 2011; Turner et al., 2014).

The solid building blocks of planets are a trace component within gas-dominated protoplanetary disks and the processes that govern the growth of macroscopic particles are not fully understood yet. Particles tend to clump due to turbulence in the disk and tend to collide, sticking together through electrostatic forces and forming larger particles, the planetesimals (Blum and Wurm, 2008).

1.3.3.2. Planetesimal Formation, Pebble and Gas Accretion

Planetesimals are intermediate-sized particles that experience forces that cause them to rapidly spiral inward, preventing their aggregation into bodies larger than a few meters size (the “meter barrier”). Eventually, some of these bodies grow by mutual collisions, forming a few massive objects, the protoplanets or planetary embryos of different mass, dependent on their distance from the host star.

The Solar System presents a good example of this different growth. The protoplanets that formed in the terrestrial zone were sub-Earth-sized bodies that underwent a velocity instability, leading to an epoch of large-scale chaos and giant impacts before settling into a more stable dynamical configuration. The objects in the asteroid

belt experienced an incomplete coagulation, probably due to the influence of the exterior planets. Just beyond the snow-line³, one or more planets may grow to $\sim 5 - 10 M_{\oplus}$ enough to capture large amounts of gas, creating the gas giants with deep atmospheres like those of Jupiter and Saturn.

The growth of planetesimals beyond the snow-line can be explained through a particular mechanism of accretion, the pebble accretion (e.g., Ormel and Klahr, 2010; Lambrechts and Johansen, 2012; Johansen and Lambrechts, 2017). Pebbles are particles that experience a strong gas drag and fall onto the protoplanets, eventually forming giant planet cores. The growth of the cores is followed by a phase of slow of gas accretion, until the mass of the gaseous envelope equals the mass of the core. After this phase, the gas accretion accelerates, building Jupiter- or Saturn- sized planets (e.g., Pollack et al., 1996).

1.3.3.3. Orbital Migration of Planets

Massive bodies (denoted generically as planets) in the disk perturb the distribution of the gas in which they are embedded. This perturbations are spiral density waves (see Fig. 1.22) that exert gravitational attraction on the planet. The balance between the torque exerted by the outer and the inner waves determines the effect on the planet.

For axis-symmetric disks, the negative torque exerted by the outer wave wins,



Fig. 1.22.: The spiral density wave launched by a planet in the gas disk. Image from Raymond and Morbidelli (2020), credits to F. Masset.

³The *snow* line, also known as the frost line or ice line, is the distance in the solar nebula from the central protostar where it is cold enough for volatile compounds such as water, ammonia, methane, carbon dioxide, carbon monoxide to condense into solid ice grains

the planet loses angular momentum and its orbit shrinks, migrating inwards. This is the Type I Migration (e.g., Cresswell et al., 2007; Paardekooper et al., 2010; Paardekooper et al., 2011). Other torques can act on the planet and affect its migration, but these processes will not be further discussed here (for a review of these processes see Raymond and Morbidelli (2020)). If the planet is big enough, it exerts a torque that can push away the gas of the disk, creating a gap that becomes deeper and wider. The formation of the gap modifies the migration rate of the planet that starts moving inwards slower. This process is known as Type II Migration (e.g., Robert et al., 2018).

1.3.3.4. Late Stage Processes

Together with the processes previously described, there also are a few processes that might influence the architecture of a planetary system as well as the water content of a planet, giving us the variety we observe in exoplanetary systems. For example, the planet-planet scattering mechanism (e.g., Ford and Rasio, 2008) could be the cause of the high eccentricities observed in some giant planet systems. Due to the dynamical instabilities in the disk, the planets in the early stages of the system cross their orbits and while one or more planets are ejected, the eccentricities of the giant planets become higher.

Another important mechanism in planet formation is the one due to the giant impacts, collisions between similar-sized massive objects (e.g., Dawson et al., 2016). Late phases of terrestrial planet growth are attributed to a small number of giant impacts between growing rocky bodies. Also the formation of the Moon could be due to a final giant impact on Earth.

Finally, some processes not discussed here are the ones related to the delivery of water from the outer regions of the Solar System (i.e. the moving snow line and drifting pebbles, the inward migration of large planetary embryos, and other) or those that dry out planetesimals and planets, such as ^{26}Al decay that provides a huge amount of heat, eventually dehydrating the bodies of the planetary systems (for a review on this topic the reader can refer to Meech and Raymond, 2019).

1.3.3.5. Different Processes, Different Models of Planet Formation

The different processes involved can give us different exoplanetary systems and interpreting what we see it is not always easy. The properties observed in the different exoplanetary systems can guide us towards the goal of explaining planet

formation and the architecture of the systems we know, but so far observational biases cloud our view. Having a general view of how planets form, helped me in my experience of characterization of an exoplanetary system, so, in this last paragraph, the current state-of-art of planet formation models will be shortly depicted. A longer discussion is beyond the purposes of this thesis, so the models will not be described in detail.

Close-in Super-Earth Formation Models for the formation of super-Earths were developed before they were even discovered. The simplest one proposes that super-Earths accreted from local material very close to the parent star. It is the in-situ accretion model (e.g., Chiang and Laughlin, 2013). In-situ accretion requires a mass of the inner disk that conflicts with measurements. Nonetheless, it has been shown that if the right conditions were to arise, accretion should indeed produce planetary systems similar to the observed super-Earths (e.g., Lee and Chiang, 2017). Another model quite successful in reproducing the observed population of super-Earths is the migration model (e.g., Carrera et al., 2018; Raymond et al., 2018a), in which large planetary embryos grow throughout the disk and migrate inward, driven by the gaseous disk.

Giant Planets Formation Two categories of formation models exist for this type of planets. In the first scenario, the disk instability model, a localized gravitational instability in the protoplanetary disk can lead to the direct formation of Jupiter-mass clumps in the outer parts of disks that migrate inward. However, it is not clear whether disk instability can produce Jupiter-like planets. For further references on this formation model the reader can refer to Boss (1997), Boss (1998) and Boss (2000).

The second model is a bottom-up scenario, the core-migration-accretion model (e.g., Johansen and Lambrechts, 2017; Bitsch et al., 2019). Giant planet cores rapidly grow thanks to the pebble accretion process and accrete gas from the disk, becoming gas giants. Simulations show that the mass scale at which the planets undergo gas accretion is the same at which migration becomes important.

Solar System Formation The classical model that assumed local growth of the planets has been revolutionized, supplanted with models that explain the distribution of the planets and small body belts. The old model had three main weaknesses: it assumed formation in place, separated for giant- and terrestrial planets, and it systematically produces Mars analogs far more massive than the real Mars (the “small Mars” problem) (e.g., Wetherill, 1991).

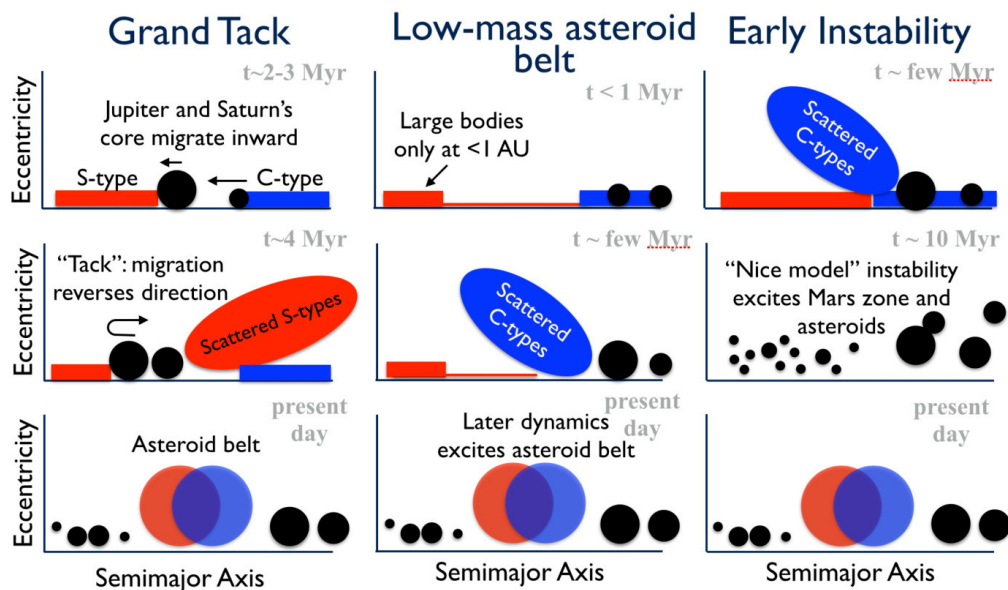


Fig. 1.23.: Cartoon view of the three competing models for how the Solar System formed. Image from Raymond et al. (2018b).

The Grand Tack model (Walsh et al., 2011) proposes that Jupiter, after its formation, migrated inward, before reversing course due to capturing Saturn in an orbital resonance, eventually halting near its current orbit.

The Low-mass Asteroid belt model (e.g., Raymond and Izidoro, 2017) instead proposes that Mars' small mass is a consequence of a primordial mass deficit between Earth and Jupiter's present-day orbits, yet rapid gas accretion onto Jupiter and later Saturn destabilized the orbits of nearby planetesimals, many of which are gravitationally scattered in all directions, filling the space currently known as asteroid belt.

The Early Instability model (e.g., Clement et al., 2019) assumes that Solar System's giant planets have undergone an instability, albeit much less violent than the typical instability incurred by giant exoplanet systems. Nonetheless, the Solar System's instability is violent enough that fully-formed the terrestrial planets would have had a very low probability of survival. The premise for this model is that the giant planets' instability took place very early after the dissipation of the gaseous disk. The instability itself is stochastic in nature and different simulation produce a great variety of Solar Systems with different properties.

Figure 1.23 shows a cartoon view of the three models for Solar System formation. The scenarios presented in this paragraph are not the only ones that have been proposed, but they give a general picture of the formation theories regarding the

architecture of the different systems, the mixing of the different processes and the challenges that must be overcome in order to match theory with observations.

Exoplanets Characterization: the Peculiar Case of Ultra-Short Period Planets

In this chapter, the efforts needed to characterize an exoplanet are presented, by combining different techniques (see Section 3.1). In Section 2.1, the importance of the mass-radius diagram in the study of small exoplanets and the different classes of planets we expect from theoretical models are illustrated. The final section 2.2 presents a particular class of rocky worlds, the ultra-short period planets, that will be further considered in Chapter 3.

2.1 The Mass-Radius Diagram

NASA's Kepler mission played a key role in making the transit method the most productive exoplanet detection technique. Performing a high relative photometric precision survey of exoplanets on a large number of stars, it reached results that shed new light on exoplanetary demography.

From Kepler's survey these important results emerged:

- Small planets with close-in orbits are common in our Galaxy; roughly half of all stars have planets intermediate in size between Earth and Neptune that orbit closer than Mercury does to the Sun (e.g., Burke et al., 2015; Dressing and Charbonneau, 2015).
- A planet radius gap, the so-called Fulton Gap (see Fig. 2.1; for further references refer to Fulton et al., 2017; Van Eylen et al., 2018) separates two distinct populations of small planets. The sub-population with smaller size planets is composed by likely rocky planets with thin or nonexistent atmospheres, while the other contains planets bigger in size with a gas rich atmosphere.
- For Sun-like stars, Burke et al. (2015) estimate a planet occurrence rate of one habitable-zone terrestrial planet for every 10 stars. For M-dwarf stars,

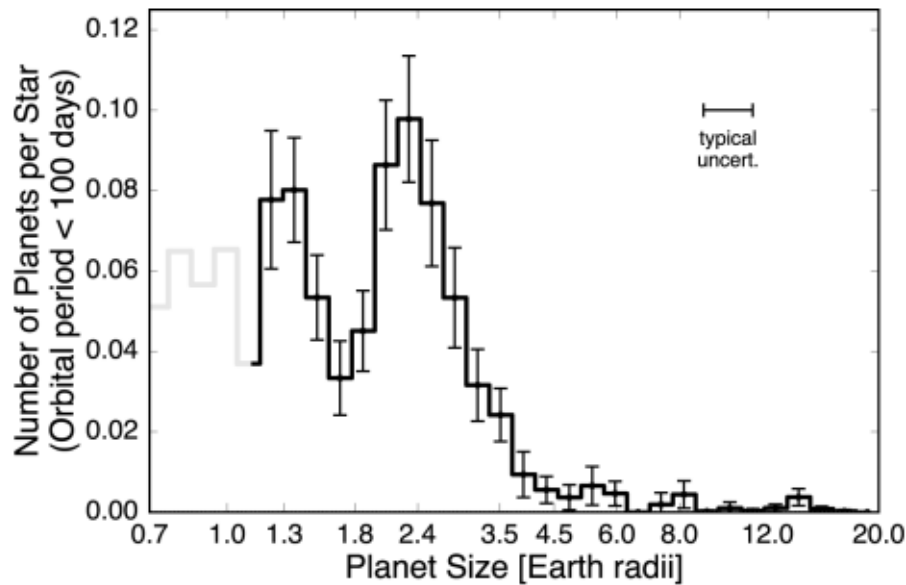


Fig. 2.1: The frequency of planets around Sun-like stars with orbital periods < 100 days as measured by Kepler. The bimodal distribution indicates two distinct populations of planets, separated by a gap (from Fulton et al., 2017).

Dressing and Charbonneau (2015) determine approximately one habitable-zone terrestrial planet for every 4 stars.

The origin of the gap is debated. Models predict that photoevaporation due to X-ray and ultraviolet (XUV) radiation, in the early stages of a star's lifetime, removes the light molecular weight envelopes of planets. The existing relationship between planet mass, surface gravity, and loss rate shows that radiation can strip the envelopes of intermediate-size planets and produce separated populations of rocky planets and more massive planets that retain their envelopes (Owen and Wu, 2017). Models also predict that the location of the gap constrains the composition of what is left after photoevaporation (Jin and Mordasini, 2018).

The combination of data from radial velocity follow up with transiting planet searches allows to fill in the mass–radius diagram of transiting extrasolar planets (Fig. 2.2) and to probe the theories of planet formation and evolution by comparing measurements to theoretical models of the internal structure. This has been particularly important for understanding the structure of the new categories of super-Earths and mini-Neptunes with masses between 3 to 10 times the mass of Earth. Planetary structure models integrate the conditions of hydrostatic equilibrium and mass conservation, using an equation of state to relate pressure to density and temperature within the planet. The precision of models for an assumed composition is limited then by the

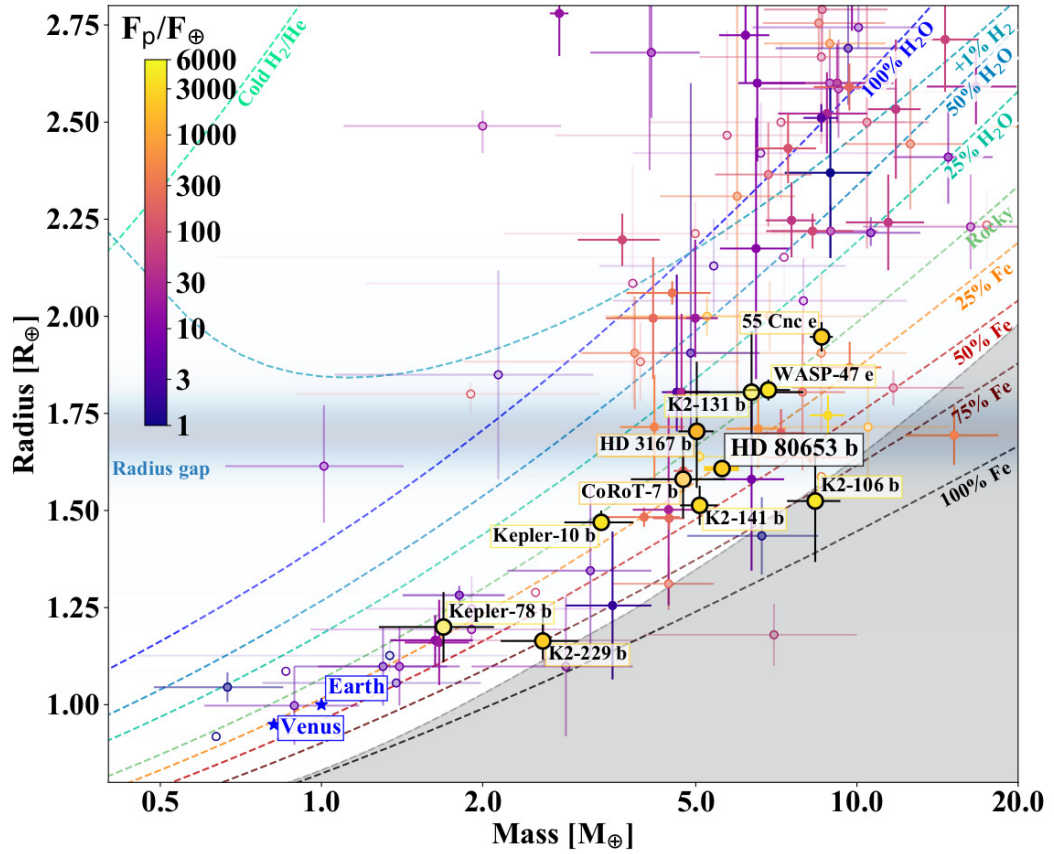


Fig. 2.2.: Mass-radius diagram of planets smaller than $\sim 2.8 R_{\oplus}$. The data points are shaded according to the precision on the mass, with a full color indicating a value better than 20%. Earth and Venus are shown for comparison. The dashed lines show planetary interior models for different compositions as labelled (Zeng et al., 2019). The horizontal light-blue shade centered on $R \sim 1.70 R_{\oplus}$ shows the radius gap. Image from Frustagli et al. (2020)

uncertainties in the equation of state, but small planets were finally divided into three main groups.

2.1.1 Deep Atmosphere Planets

Low-mass planets whose volumes are dominated by H/He gas are the planets with the bigger radius. However, this does not mean that a significant fraction of their mass is in the form of gas. The bulk density of a planet strongly depends on its temperature profile as well as its composition. (Lopez and Fortney, 2014) showed that an envelope mass fraction as low as a few per cent can cause a $3 M_{\oplus}$ planet to have a radius as large as $3 R_{\oplus}$ for a wide range of ages and incident fluxes.

The size of these planets is then affected by the cooling of the envelope, highly dependent on the incident flux and the composition, since a mostly rocky planet has a higher heat capacity than one in which volatiles are the dominant species. Moreover, ionizing X-ray/extreme ultraviolet (EUV) fluxes heat the highest levels of the atmosphere, inducing hydrodynamic winds that remove gases and heavier elements. Strong constraints on age can help to better understand the evolution of the planet and the atmospheric mass loss over its lifetime, although the X-ray/EUV flux rapidly declines by a factor ~ 25 from 100 Myr to 1 Gyr in age (Ribas et al., 2005) and then most of the evolution is expected to occur in the first few 100 Myr.

2.1.2 Water World Planets

Models that describe the radius of water-rich planets contain some theoretical uncertainty. Older models (e.g., Fortney et al., 2007) differ by $\sim 10\%$ for a given mass from more recent ones (e.g., Zeng and Sasselov, 2013). However, some studies generally neglect the contribution to pressure in the equation of state from thermal effects, which explains some of the discrepancy between the results.

The effect of thermal pressure on the size of a water-rich planet of a particular mass was tested by Thomas and Madhusudhan (2016). According to their models, water worlds have planetary radii sensitive to the temperature of the water layers. Thus, for a given mass and water-rich composition, planetary models require either an assumed thermal profile or a detailed cooling model.

2.1.3 Rocky Planets

The Earth’s density profile is the benchmark model of rocky exoplanets. In planetary interiors, phase transitions are a source of uncertainty for planets with unknown temperature profiles and can cause discontinuities in the equation of state. Theoretical models of rocky planets up to $10 M_{\oplus}$ can differ by up to $\sim 2\%$ in radius depending on the equation of state used in the iron core (e.g., Smith et al., 2018) and by up to $\sim 2\%$ depending on the equation of state used in the mantle (e.g., Zeng et al., 2016).

Earth’s ratios of non-volatiles have long been assumed to match chondritic meteorites, which in turn are closely consistent with elemental abundances in the Sun (e.g., Brown, 1950; Hurley, 1957). Thus, a wide variety of plausible compositions opens for rocky exoplanets. Indeed, rocky planets do not need to have an Earth-like composition if their hosts have different abundance ratios among Fe, Si, Mg, C and O than does the Sun (e.g., Bond et al., 2010). Moreover, Mercury is an example of a planet that does not match the abundance ratios of its parent star.

However, theoretical differences in composition based on stellar abundances can be used as a prior in models of planetary structure (e.g., Dorn et al., 2017), but it is worth noting that exoplanetary masses and radii are not yet characterized precisely enough for such differences to be tested.

2.2 Ultra-short Period Planets

The sample of characterized exoplanets with radii smaller than $2 R_{\oplus}$ is growing and this allows us to probe the transition from planets with densities consistent with mixtures of rock and metal to those that must retain substantial volumes of gas.

Among exoplanets that have a radius whose length is shorter than $2R_{\oplus}$, and appear to have an Earth-like composition (Winn et al., 2018), with also some evidence for planets with iron-rich compositions (e.g., Santerne et al., 2018), the so-called ultra-short period (USP) planets are expected to be very rewarding. These planets orbit around their parent stars with extremely short periods ($P \leq 1$ d).

The origin of this sub-population is still unclear, with different formation scenarios highly dependent on models. As the sample of USP planets grows, this might help us to understand the formation and orbital evolution of short-period planets, as well as star-planet interactions, atmospheric erosion, and other phenomena arising from strong stellar irradiation and tidal forces. Moreover, there are some practical advantages to studying USP planets. Compared to exoplanets with the same sizes and masses but in wider orbits, they are easier to detect and their physical parameters

are easier to measure. Some of them are also hot enough to emit a detectable glow, enabling observations to determine their surface temperature and reflectivity (e.g., Malavolta et al., 2018; Frustagli et al., 2020).

As we learn more from USP planets observations, new investigations on their properties bring us new knowledge and we understand more about their origin and evolution, probing the modern theories of planetary physics.

2.2.1 Orbital Architecture

For such close-in planets, huge tidal interactions lead to relatively rapid orbital and spin evolution. Therefore, for USP planets orbiting around a mature main-sequence star, it is reasonable to assume the circularization of the orbit (e.g., Matsumura et al., 2008) and a permanent dayside and nightside.

Applying Kepler’s third law, we obtain the scale of the orbit:

$$a = 0.0196 \text{ AU} \left(\frac{P_{\text{orb}}}{1 \text{ day}} \right)^{2/3} \left(\frac{M_{\star}}{M_{\odot}} \right)^{1/3} \quad (2.1)$$

$$\frac{a}{R_{\star}} = 4.2 \left(\frac{P_{\text{orb}}}{1 \text{ day}} \right)^{2/3} \left(\frac{\rho_{\star}}{\rho_{\odot}} \right)^{1/3} \quad (2.2)$$

According to theoretical calculations, the orbit of an USP planet does not have enough angular momentum to achieve a stable double-synchronous state. The planet is then expected to spiral into a timescale dependent on the planetary modified tidal quality parameter, but it is not clear whether tidal orbital decay becomes important on long timescales.

2.2.2 Period Distributions

It is worth noting that the defining criterion of $P \leq 1 \text{ d}$ is arbitrary and there is no astrophysical reason to distinguish between planets inside and slightly outside this boundary. Lee and Chiang, 2017 pointed it out, showing that the occurrence rate for planets with radii larger than $2 R_{\oplus}$ changes slope at around 10 days (see Fig. 2.3).

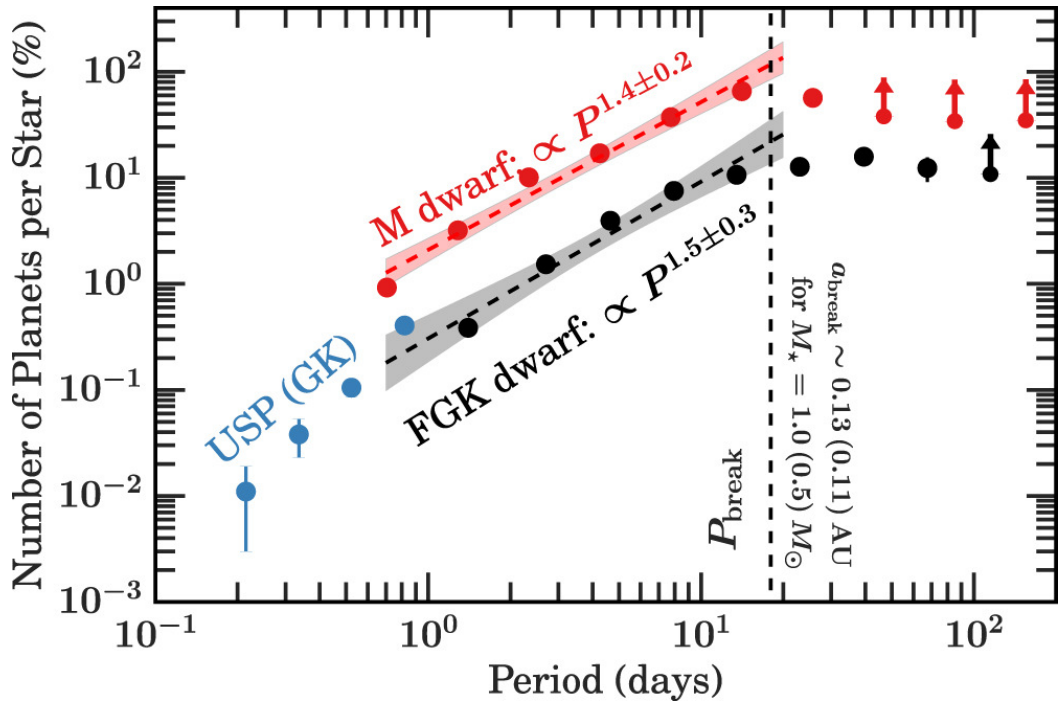


Fig. 2.3.: Occurrence rates of sub-Neptunes ($R < 4R_{\oplus}$) orbiting FGK dwarfs and early M dwarfs. A distinctive break at $P_{\text{break}} \sim 10$ days divides long-period planets from their short-period counterparts. Ultra-short period planets are highlighted in blue. Source: Lee and Chiang (2017).

2.2.3 USP Occultations

When an exoplanet passes behind its host star, the total flux of the system decreases by an amount proportional to the average brightness of the planet's dayside. The depth of the secondary eclipse is a combination of reflected light and thermal emission. The estimation of the planet's dayside temperature is necessary to extrapolate the thermal flux to the optical wavelengths, in order to isolate the contribution from the reflected light and to measure the geometric albedo.

Detecting the secondary eclipse of small exoplanets is a very challenging task; Kepler data allowed us to detect it in optical wavelengths just for a few USP planets, namely Kepler-10 b (Batalha et al., 2011), Kepler-78b (Sanchis-Ojeda et al., 2013), and K2-141b (Malavolta et al., 2018). Strong hints of a secondary eclipse were also found for HD 80653 b by Frustagli et al. (2020).

In the next future, precise space-based photometry (e.g. JWST, CHEOPS) is expected to be very useful in the detection of secondary eclipse for more USP planets, helping to unveil the nature of this interesting sub-population of exoplanets.

2.2.4 Longer Period Companions

A significant fraction of USP planets are associated with longer-period planetary companions. This conclusion is based on the detections of multi-transiting systems with both longer-period planets and USP planets. The expectation, based on a statistical argument involving the dependence of transit probability on orbital period, remains that most of these systems do not contain transiting outer planets (Sanchis-Ojeda et al., 2014).

Observations suggest that some process has widened the period ratio (see Fig. 2.4). Indeed, when the inner planet has a period shorter than one day, the period ratio between the outer and inner planets is almost always greater than 3.

The comparison between the transit impact parameters of planets in the same systems also suggests that they appear to have higher mutual inclinations (Petrovich et al., 2019). This finding could be a hint of secular gravitational interactions leading to excitation of the inner planet's inclinations.

2.2.5 Formation Theories

The origin of USP planets is still unclear, with several formation scenarios that lead to different predictions for their final compositions and for the properties of any

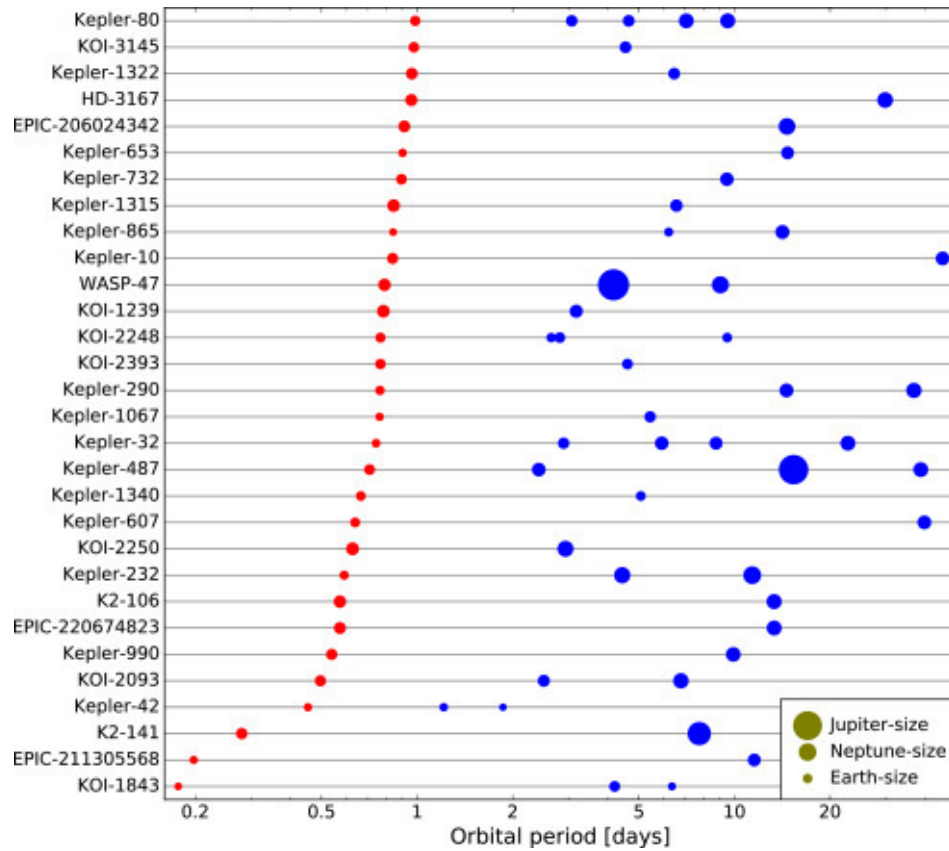


Fig. 2.4.: Ultra-short-period planets associated with multi-planet systems. Source: Winn et al. (2018).

additional planets around the same star.

In recent years, several theories have been offered and just a few of them withstand as the sample of USP planets grows:

1. The planets form from solid material that collects near the innermost edge of the protoplanetary disk. For Sun-like stars, the inner edge is the distance at which the orbital period matched the stellar rotation period and that corresponds to 10 days for early ages. This “in situ accretion” process would result in a dry composition and explains the occurrence rate dropping observed.
2. Another possibility is the spiraling-in of a planet, due to gravitational interactions the disk (Type I migration) or with nearby planets in wider orbits. The first scenario predicts resonant chains of multiple planets, but such chains are infrequent in the Kepler sample and no USP planet are involved. The second scenario predicts instead the shrinkage of the orbit until tidal interactions with the stars set in and the planet spirals-in so close that it becomes an USP planet. However, this case predicts that USP planets should be more common around massive (F-type) stars than around lower-mass stars, but observations appear to go in the opposite direction.
3. The evolution of USP planets due to eccentricity excitation from secular dynamical chaos in compact multiplanet systems is another intriguing case. Petrovich et al. (2019) predicted that USP planets are generated by initially wide-orbiting planets and that they would show mutual inclinations with respect to the orbits of outer planets.
4. According to other hypotheses, USP planets are formerly gaseous planet that approached the star too closely and underwent strong photo evaporation (e.g., Owen and Wu, 2013; Ehrenreich et al., 2015; Winn et al., 2017), ending up with the removal of their gaseous envelope and their solid core exposed. This scenario could explain the radius gap as being due to highly irradiated, close-in planets losing their gaseous atmospheres, while planets on longer period orbits, not being strongly irradiated, are able to retain their atmospheres (Owen and Wu, 2017; Fulton et al., 2017; Van Eylen et al., 2018). The problem is that this theory by itself does not explain where the progenitor planet came from.

Exoplanets Characterization: the HD 80653 b Case

In this chapter, I present my work regarding the characterization of exoplanets, showing the analysis I have done with the HARPS-N Collaboration. Finally, in Section 3.3 I conclude with a summary of my experience in exoplanets characterization during the three years of the PhD course.

3.1 Combining Transit Photometry and Radial Velocity Data: the HARPS-N Collaboration

Several methods for detecting exoplanets have been developed and since 1995 clever innovations have advanced their precision. These techniques are lenses through which we detect exoplanetary systems, but each of them have inherent observational incompleteness. In principle, the techniques are complementary; in practice, they are generally applied to different samples of stars and then it is difficult combining them. However, there is a definite symbiosis between transit observations and radial velocimetry. On the one hand, velocimetry is needed to establish the true nature of the transit candidates, while on the other, transiting systems have an orbital inclination on the sky $i \sim 90^\circ$, allowing the degeneracy to be lifted on the minimum mass provided by velocimetry.

The space missions CoRoT (Baglin et al., 2006) first, Kepler (Borucki et al., 2010) then and TESS (Ricker et al., 2014) now are dedicated to the search of transiting exoplanets by collecting long, high-precision photometric time series of thousands of stars. Transit events have to pass first through a series of photometric and spectroscopic tests to exclude alternative scenarios before they can be confirmed as transiting planets. Only after these tests, it is possible to determine the planet-to-star radius ratios and hence the size of the planets

Spectroscopic measurements of the host star's radial-velocity variations are then required to determine the masses of the transiting objects and eventually rule out

grazing transits of binary stars and stellar blends, which could mimic a planetary transit signal.

Consequently, knowledge of the masses of exoplanets is essential both as a diagnostic of planetary nature and as a tracer of planetary origins. A planet's ability to form and retain an atmosphere, the strength of its dynamical interactions with other bodies, and its initial gravitational energy all depend on mass. Therefore, it is probably the most fundamental property of a planet.

The HARPS-N collaboration was established with the objective of putting together the efforts of various institutes of different countries for the construction and operation of a high-resolution spectrograph able to discover and characterize terrestrial exoplanets by achieving long-term 1 meter per second median radial-velocity precision on $V < 11$ mag stars.

The collaboration has three broad scientific goals:

1. Characterizing super-Earths in various orbits with enough precision to distinguish between volatile-rich and predominantly iron-silicate planets;
2. Measuring accurate masses to a precision of 10% or better, for planets at which the transition between super-Earths and Ice Giants occurs;
3. Confirming an Earth-twin planet in the habitable zone of a G5V star or later, with a precision of 30% in mass.

In order to pursue these goals, the collaboration uses the HARPS-N high-resolution spectrograph operating at the Telescopio Nazionale Galileo (TNG) in synergy with data from space missions like Kepler/K2 and TESS. The best-suited targets for radial velocity follow-up are observed with HARPS-N and the planets are then characterized with high precision.

3.2 Characterization of an USP Planet: the HD8053b Case

HD80653 star was observed by K2 for about 80 days between 2017 December 9 and 2018 February 25 and a planet candidate was originally identified in the K2 raw data by Yu et al. (2018). In the next Paragraphs I will show in details the analysis of the photometric data for this system, that we used to characterize the star and the orbital parameters of the planet.

3.2.1 K2 Photometry

Following the procedures described by Vanderburg and Johnson (2014) and Vanderburg et al. (2016), we extracted the light curve from the calibrated pixel files. The technique to reduce K2 data uses a “self-flat-fielding” (SFF) approach, re-deriving the K2 systematics and simultaneously modeling the spacecraft roll systematics, planetary transits, and long term variability. This improving raw K2 photometry by a factor of 2-5 and showing no evidence for distortions.

We used a Box Least Squares (BLS) transit search pipeline (Kovács et al., 2002;

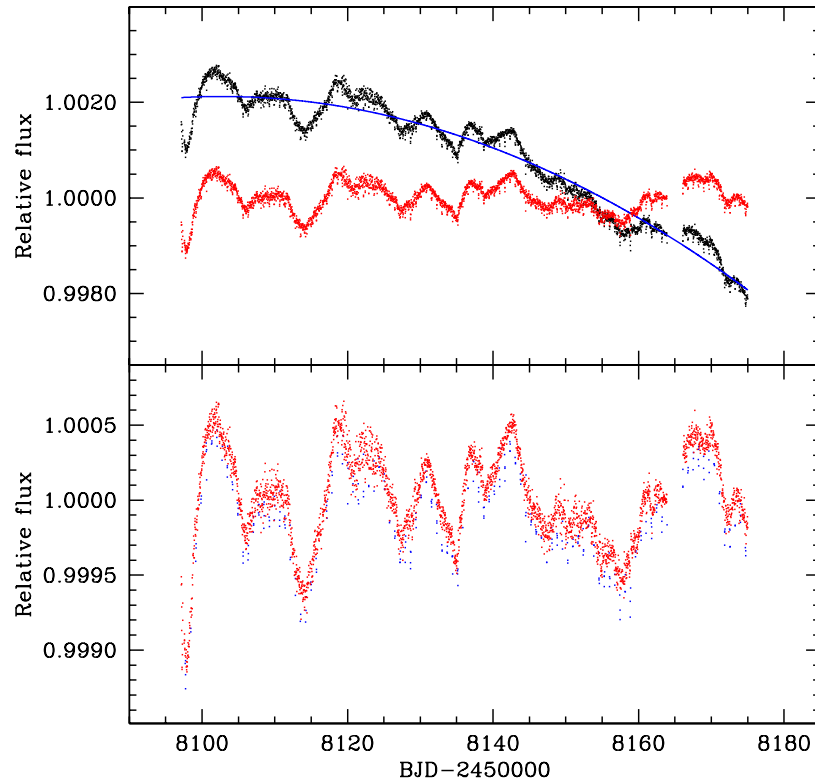


Fig. 3.1: K2 photometry of HD 80653 b. *Top panel:* light curve extracted from the MAST raw images (black dots), second-order polynomial fit of the long-term instrumental trend (blue line), corrected light-curve (red dots). *Bottom panel:* corrected data (red dots) with highlighted measurements obtained during transits (blue dots).

Vanderburg et al., 2016); this algorithm analyzes stellar photometric time series and searches for signals characterized by a periodic alternation between two discrete levels, guaranteeing high level performances. We confirmed the previous detection (see Fig. 3.3) and obtained measurements that show a continuous decrease, probably due to an instrumental drift (black dots in the top panel of Fig. 3.1). We removed the drift (blue line) using a second-order polynomial and obtained the stellar photo-

metric behaviour of HD 80653 (red dots).

The bottom panel of Fig. 3.1 shows the corrected data in red and the measurements obtained during transits in blue. A preliminary analysis detected the transits, with a $P_b=0.7195$ d and a duration of 1.67 h, superimposed on low-frequency flux variations with a peak-to-valley variability of $\sim 0.1\%$, likely due to the rotational modulation of photospheric active regions on the stellar surface.

3.2.1.1. Studying the Star, Knowing the Planet: Analyzing Stellar Activity using Photometry

Because most exoplanets are discovered by indirect means, it is often said that you can only know a planet as well as you know the host star. Stellar variability, caused by physical processes which have different time scales, is a source of correlated noise superimposed onto the planet signal in the stellar light curve and radial velocity curve. Stellar magnetic activity, due to differential rotation between the stellar core and the stellar convective envelope for main sequence stars, is the main cause of stellar variation and causes the presence of regions where the hot material emerges from the sub-surface making the surface appear brighter (plages) and regions where cooled material sinks back into the stellar surface, with the surface appearing darker (spots). As the star rotates, both the stellar spots and plages appear and disappear on the visible side of the star, which changes the stellar brightness at the timescale of the stellar rotation. The number of spots and plages also evolve in time over longer timescales. These stellar variations produce photometric and spectroscopic stellar variability on time scales from days to weeks (stellar rotation) and from month to years (stellar activity cycles), giving signals comparable or larger than the amplitude of the planetary perturbation and preventing the detection and mass characterization of small-mass planetary candidates.

We examined the data more in detail in order to gather more information about the star behaviour. Indeed, Fig. 3.1 shows modulated rotational cycles due to active regions on the stellar surface. In particular, around BJD 2458145, we noted a standstill at the level of the average flux that seems to strongly modify the shape of the light curve. We decided to further investigate this interesting behaviour. First, we removed the in-transit measurements. Then we performed three different frequency analyses; we analyzed the whole dataset and then two subsets: the first composed of the measurements before BJD 2458145 and the second composed of those after BJD 2458145.

The Generalized Lomb Scargle (GLS) spectra (see Fig. 3.2) suggest a rotational modulation with $f_{\text{rot}}=0.055 \text{ d}^{-1}$ and harmonics in the first subset and $f_{\text{rot}}=0.037 \text{ d}^{-1}$

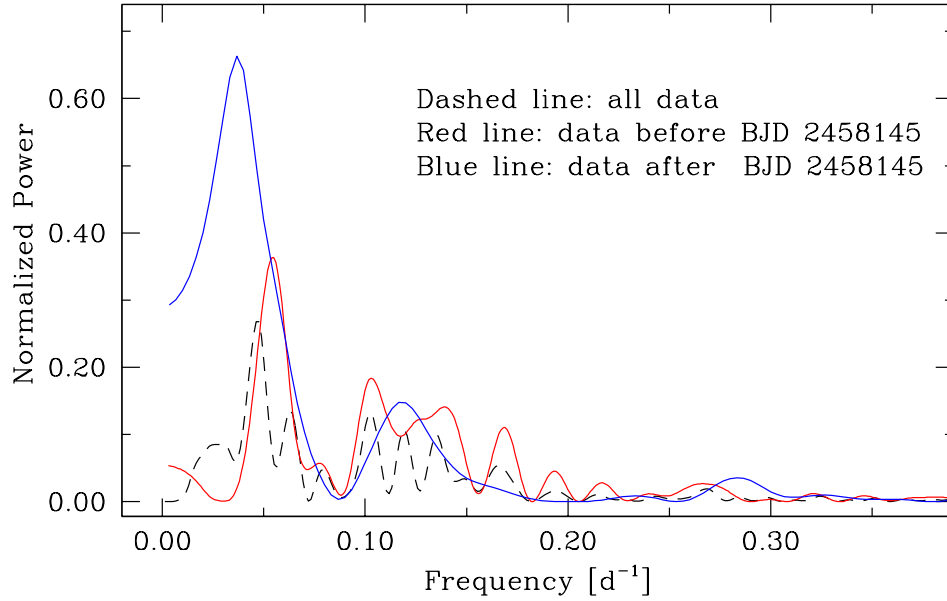


Fig. 3.2.: GLS Power spectra of the K2 data. The full data set has been subdivided into two subsets, before and after BJD 2458145. Two different rotational frequencies are then detected. The power spectrum of the full data set appears as an average of the two.

and harmonics in the second subset. The presence of harmonics indicates a double-wave shape over the rotational period, indicating that the star is seen nearly equator-on with activity in both hemispheres. The frequencies correspond to $P_{\text{rot}}=18$ d and 27 d, respectively, with the latter value poorly constrained due to the short time coverage of K2 photometry. The power spectrum of the full data set does not supply useful hints, since several peaks appear as the merging of the incoherent frequencies detected in the two subsets.

3.2.1.2. Planet Characterization using Photometry: Primary Transit

Exoplanet detection is only the first step, their characterization is the logical next step. Each detection method only gives partial information, so when a particularly interesting planet is detected, astronomers try to combine several method to confirm and characterize it. The synergies between the different technique are essential to understand the astonishing diversity of these foreign worlds.

Measuring a transit gives access to a number of physical parameters: the depth of the transit provides info on the planet-star radius ratio, the shape of the transits provides information on the impact parameter and thus on the orbital inclination, while the

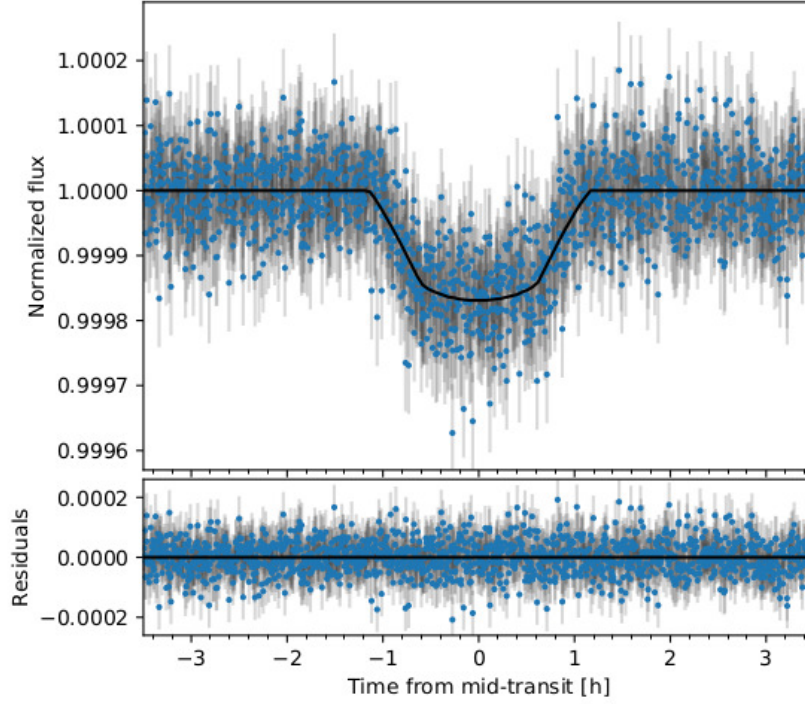


Fig. 3.3.: *Top:* HD 80653 b transit light curve phase-folded to a period of $P_b = 0.719573$ d, as determined using PyORBIT. *Bottom:* The residuals of the transit fit.

total duration further constrains the ratio $\frac{R_\star}{a}$ as a function of the eccentricity and the angle of periastron, and when the latter are known, the stellar density.

Several factors allowed us to clearly detect the planetary transits in K2 light curve. First, the limited variability ($\sim 0.1\%$) of HD 80653. Second, the sharpness of the transits. Last, due to the ultra-short orbital period, the transits have been observed at almost all the stellar activity levels, thus making very effective the cancellation of the effects produced by unocculted small spots and faculae.

We used the flattened K2 light curve to perform the transit fit employing PyORBIT (Malavolta et al., 2016; Malavolta et al., 2018). We assumed a circular orbit for the planet, basing our assumption on the extremely short circularization time for such a close-in planet, i.e. < 0.5 Myr (Matsumura et al., 2010). We also applied a parametrisation for the limb darkening (Kipping, 2013) and imposed a prior on the stellar density directly derived from the posterior distributions of $M_\star$ and $R_\star$. An eccentric orbit would be highly unlikely because the planetary orbit would circularize very quickly and a Keplerian fit with no assumption on the eccentricity returned a value consistent with zero. PyORBIT relies on `batman` (Kreidberg, 2015), a versatile code to generate model transit light curves. Following the prescriptions by Kipping (2010), we adopted an oversampling factor of 10 when accounting for the 1764.944 s

exposure time of the K2 observations, in order to avoid distortions to the transit light curve induced by finite integration times or equivalently temporal binning. Correcting this effect is very important, because it leads to longer transit durations and more V-shaped transits, and as a consequence we obtain ratios between the semi-major axis and the stellar radius lower than the true ones. In turn, this yields lower stellar densities from the third Kepler law and thus both stellar and planetary radii appear larger than they actually are. From the posterior sampling used by `PyORBIT`, that contains an affine-invariant Markov chain Monte Carlo emcee sampler (Foreman-Mackey et al., 2013), we obtained an orbital period $P_b = 0.719573 \pm 0.000021$ d and a reference central time of transit $T_c = 2458134.4244 \pm 0.0007$ BJD.

To determine the planet radius, the brightness drop of the parent star that occurs during the planetary transit is measured. Since the brightness drop is directly related to the ratio of the planet radius to the radius of the star, given the stellar radius of HD 80653 given in Table 3.3 we derived $R_b = 1.613 \pm 0.071 R_\oplus$.

We also ran a fit using the raw light curve and modelling it with a Gaussian Process through the `celerite` package (Foreman-Mackey et al., 2017). The results were perfectly consistent with the results from the pre-flattened light curve. Fig. 3.3 shows the phase-folded light curve with the best fit.

Rossiter-McLaughlin Effect In Paragraph 1.1.2.2 of Chapter 1, I presented the Rossiter-McLaughlin effect. To a first order, its semi-amplitude scales with the planet’s size and the stellar rotational velocity:

$$A_{\text{RM}} = \frac{2}{3} \cdot d \cdot v \sin i \sqrt{1 - b^2} \quad (3.1)$$

where $d = (R_p/R_\star)^2$ is the transit depth, v is the rotational velocity of the star at the equator, $\sin i$ is the inclination on the sky of the stellar rotation axis, and b is the impact parameter (in units of $R_\star$).

According to the values of $v \sin i$, transit depth and impact parameter obtained for HD80653 b, the expected semi-amplitude for the Rossiter-McLaughlin effect is $47 \pm 10 \text{ cm s}^{-1}$ and it is therefore smaller than our σ_{RV} errors ($\text{RMS} = 7.71 \text{ m s}^{-1}$). Hence, it is not possible to measure this effect with HARPS-N spectrograph, while it could be done with next generation spectrographs.

3.2.1.3. Planet Characterization using Photometry: Secondary Eclipse and Phase Curve

When the planet's orbit carries it out of view, the light from the planet is blocked and the total system flux decreases by an amount proportional to the average brightness of the planet's dayside. The secondary eclipse is harder to detect than a transit, as the planet is much fainter than its host star, but both signals give valuable information: from a secondary eclipse we actually gain insight into several physical characteristics of the planet such as its atmosphere thermal structure, its averaged dayside emission, and a precise measurement of the orbital eccentricity.

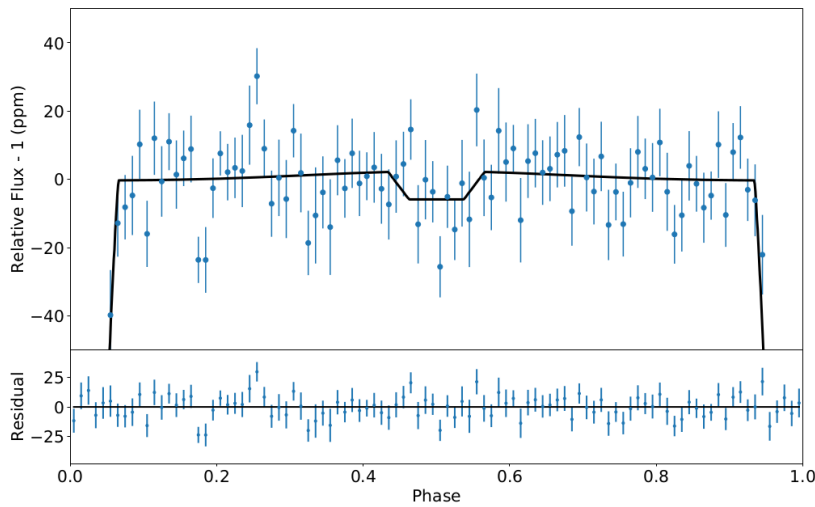


Fig. 3.4.: Phase-folded secondary eclipse with the best-fit model and the residuals at the bottom. The data has been binned by a factor of 100 for clarity.

Kepler data have also allowed to detect the optical occultations and the flux variations along the orbital phase for just a few USP planets, namely Kepler-10b (Batalha et al., 2011), Kepler-78b (Sanchis-Ojeda et al., 2013) and K2-141b (Malavolta et al., 2018). Under the assumption that the secondary eclipse is mainly due to the planet's thermal emission in the Kepler bandpass for the high day-side temperature, we were able to put some constraints on the nature of HD 80653 b, by comparing the depth of the secondary eclipse, δ_{ec} , and the amplitude of the flux variations along the phase, A_{III} .

We used the filtered K2 light curve and we simultaneously modeled the primary transit, the secondary eclipse, and the flux variations along the phase. The model

we adopted follows the one by Mandel and Agol (2002) and assumes a circular orbit, fixed the quadratic limb darkening coefficients to the values previously found for the transit and no limb darkening for the secondary eclipse. For the flux variations we followed the prescriptions by Esteves et al. (2013) and considered the normalized, out-of-transit phase curve as the sum of four contributions, namely the planet’s phase function, the secondary eclipse, the Doppler boost caused by the host star’s changing radial velocity, and the ellipsoidal variations resulting from tides on the star raised by the planet. For this particular case, the third and fourth contributions are negligible and hence were not incorporated in our model.

As in Sect. 3.2.1.2, we adopted a short-cadence (1 min) binning in order to overcome the distortions of the transit shape due to the long-cadence temporal sampling. We employed a differential evolution Markov chain Monte Carlo technique (DE-MCMC; Ter Braak, 2006) as implemented in the EXOFASTv2 code (Eastman et al., 2013; Eastman, 2017) to derive the posterior distributions of the fitted parameters (Fig. 3.5).

The values and uncertainties obtained for the primary transit parameters are fully consistent with those determined in Sect. 3.2.1.2. Furthermore, the procedure pointed out a possible secondary eclipse with a depth of $\delta_{\text{ec}} = 8.1 \pm 3.7$ ppm at 0.50 of the planet period P_b (Fig. 3.4). Despite the large uncertainty on δ_{ec} , we are confident that this result indicates the detection of the secondary eclipse and not noise due to the stellar activity or background objects: as expected, the signal of the planet is found at 0.5 in phase, it has approximately the same duration as the primary transit, and it has an amplitude consistent with the planet thermal emission. Statistically speaking, we computed the values of the Bayesian Information Criterion (BIC; Liddle, 2007) for the two models with and without the secondary eclipse, in order to understand which one is favored. We obtained $\Delta\text{BIC}=5.2$ and hence a Bayes factor $B_{10} \sim 13.5$ in favor of the former (Burnham and Anderson, 2004). By using appropriate guidelines (see Sect. 3.2 in Kass and Raftery, 1995), this value provides a positive evidence for the detection of the secondary eclipse, but because of the large relative uncertainty on the occultation depth, we could not reach the threshold for a strong detection ($B_{10} = 20$).

The flux variations along the phase are not detected since their amplitude is consistent with zero: $A_{\text{ill}} = 2.7 \pm 3.5$ ppm. Despite the large uncertainty on δ_{ec} and assuming a pure reflecting planet without thermal emission, we estimated the planet geometric albedo as a function of the day-side temperature (Fig. 3.6) in the Kepler bandpass (Rowe et al., 2006).

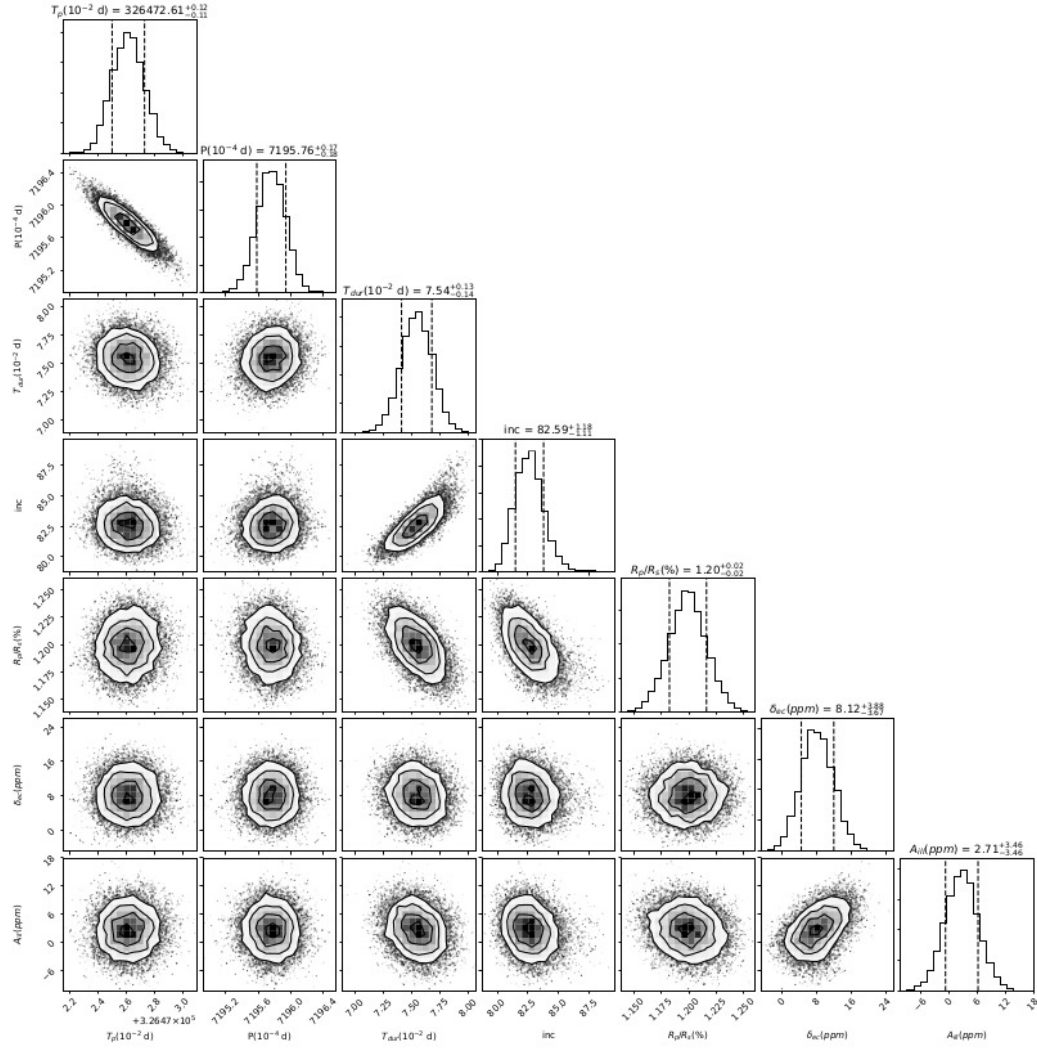


Fig. 3.5.: Posterior distributions of the best-fit DE-MCMC parameters estimating a secondary eclipse of 8.1 ± 3.7 ppm and flux variations along the phase consistent with zero within $1\text{-}\sigma$

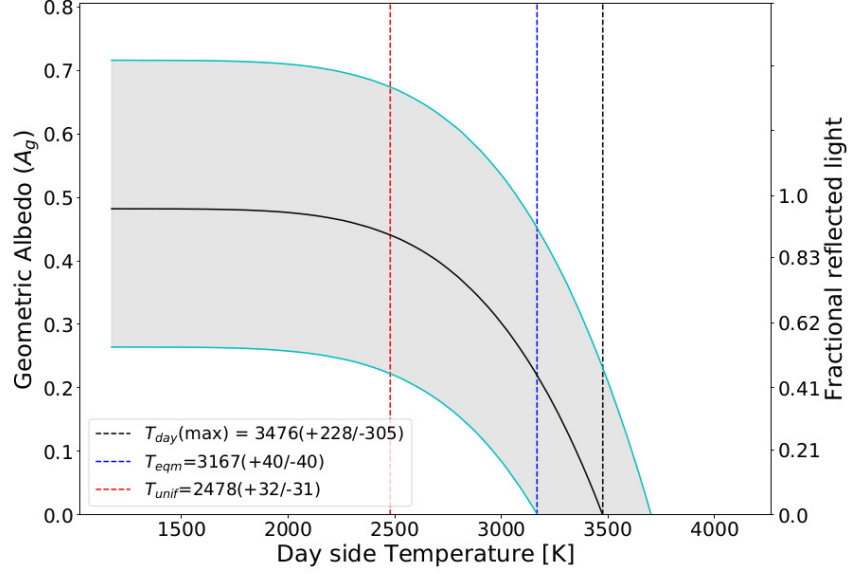


Fig. 3.6.: Geometric albedo vs day-side temperature. The dashed lines correspond to the maximum planet day-side temperature (black), the equilibrium temperature in the no-albedo and no-circulation limit (blue) and the uniform temperature for a null Bond albedo and extreme heat circulation (red). The shaded grey region displays the 1- σ interval for the geometric albedo.

Even in the optical, part of the observed light from the planet could be due to thermal emission (e.g., López-Morales and Seager, 2007; Snellen et al., 2009). The observed secondary eclipse depth is a combination of the reflected light and the thermal emission:

$$\delta_{ec} = \frac{F_{th}}{F_{\star}} + \frac{F_{ref}}{F_{\star}} \quad (3.2)$$

where F_{th} is the thermal flux generated by the planet and F_{ref} is the reflected light. However, owing to its proximity to the host star (1/60 AU) and the host star being brighter than our own Sun (a factor of 1.67 times the bolometric luminosity of the Sun), HD 80653 b receives a bolometric irradiation (radiation flux received per unit surface area) about 6,000 times larger than the insolation at the Earth's surface. Since the planet is highly irradiated, the most important contribution to the secondary eclipse might come from the the day-side thermal emission rather than the light reflected by the planet surface expected and we can estimate the thermal flux of the planet assuming a blackbody emission. For tidally locked planets and assuming black-body emission, Cowan and Agol (2011) proposed the following expression to calculate the day-side temperature:

$$T_d = T_{\text{eff}} \sqrt{\frac{R_\star}{a}} (1 - A_B)^{\frac{1}{4}} \left[\frac{2}{3} - \frac{5}{12} \epsilon \right]^{\frac{1}{4}} \quad (3.3)$$

where the Bond albedo A_B is fixed to zero and ϵ is the circulation efficiency. We used this formula for HD 80653 b and Figure 3.6 shows what theoretical calculations predict. The maximum achievable day-side temperature could be $T_{\text{day}}(\text{max}) = 3476_{-305}^{+228}$ K for a null Bond albedo and the vertical lines indicate the theoretical variations of the temperature when the circulation efficiency is allowed to vary from a full redistribution of the energy budget ($\epsilon = 1$) from the day-side to the night-side to no heat circulation in the atmosphere ($\epsilon = 0$).

The maximum night-side temperature predicted assuming a null Bond albedo and efficient circulation is $T_{\text{unif}} = 2478_{-31}^{+32}$ K, indicating a non-negligible night-side emission. This would be at odds with the lava-ocean planet model elaborated by Léger et al. (2011) that predicts inefficient circulation, but two reasons prevented us from drawing any firm conclusion. First, the large uncertainties on the amplitudes of the secondary eclipse and of the flux variations along the phase. Secondly, the well-known degeneracy between reflected and thermal light in the Kepler optical bandpass (Cowan and Agol, 2011). Precise space-based photometry (e.g., JWST, CHEOPS) would be extremely useful to unveil the nature of this USP super-Earth.

3.2.2 HARPS-N High Resolution Spectroscopy

Once the planet candidate was confirmed, the HARPS-N Collaboration's included it in its Guaranteed Time Observations (GTO) program with the goal of precisely determining its physical characteristics. We collected 115 spectra from November 2018 to May 2019 with the HARPS-N spectrograph (R=115 000) installed on the 3.6-m Telescopio Nazionale Galileo (TNG), located at the Observatorio del Roque de los Muchachos in La Palma, Spain (Cosentino et al., 2012). Due to the short orbital period, we took between 2 and 4 spectra per night on several nights, with an exposure time of 900 s, maximizing the information on the amplitude and removing at the same time activity variations. Seven spectra with low signal-to-noise ratio ($S/N < 40$) taken on two nights were no longer considered. The 108 remaining spectra have S/N in the range 40–127 (median $S/N = 84$) at 550 nm. The RV errors are photon-limited with an average RV error of 1.37 m s^{-1} whilst the RMS of the RVs is 7.71 m s^{-1} .

The spectra were reduced with the version 3.8 of the HARPS-N Data Reduction Software (DRS), which includes corrections for color systematics introduced by

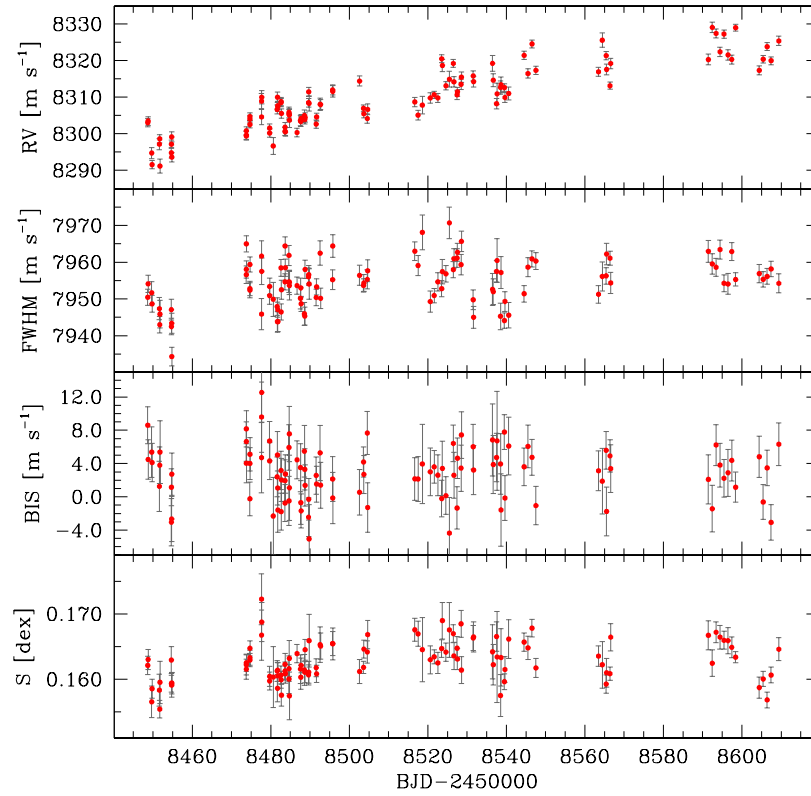


Fig. 3.7.: Radial velocities and stellar activity indicators time series extracted from HARPS-N spectra. The positive long-term trend is a strong feature in the RV time series, with no counterpart visible in the indicators. It could indicate the presence of an outer companion.

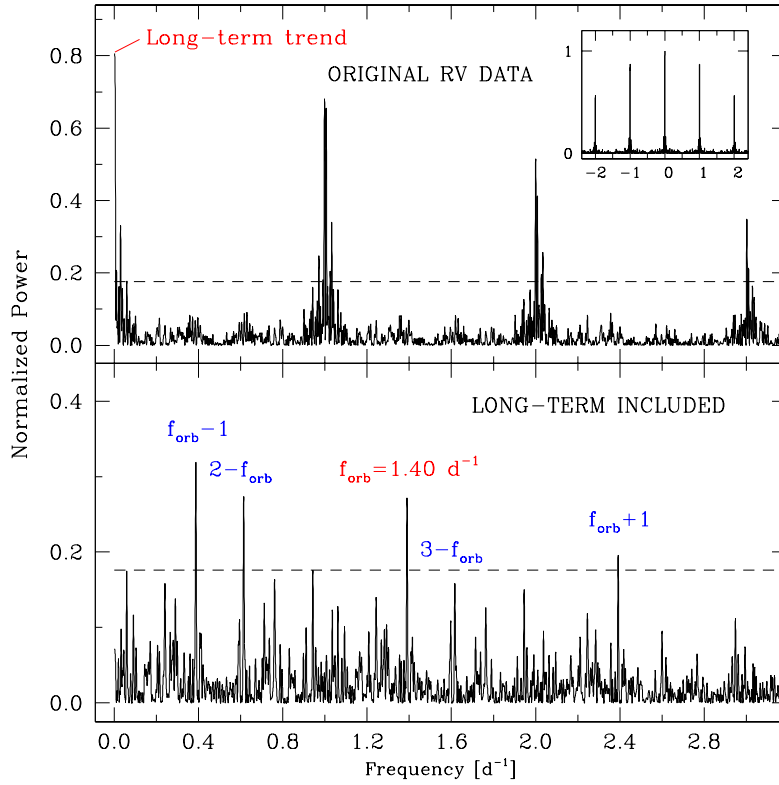


Fig. 3.8.: ISW power spectra of the HARPS-N radial velocity data. The horizontal line marks $\text{FAP}=1\%$. *Top panel:* the long-term trend is the main feature in the original data. The insert shows the spectral window of the data. *Bottom panel:* the orbital frequency of HD 80653 is clearly detected when a quadratic trend is added as a known constituent.

variations in observing conditions (Cosentino et al., 2014). The DRS calculated the weighted cross correlation function (CCF; Pepe et al., 2002) using a numerical weighted G2 mask, also providing some activity indicators, such as the full width at half maximum (FWHM) of the CCF, the line bisector inverse slope (BIS) of the CCF, and the Mount Wilson S-index (S_{MW}). The time series of the RVs and activity indicators are shown in Fig. 3.7. Error bars on the FWHM and BIS values have been taken as twice those of the RV ones following the prescription by Santerne et al. (2018).

We performed a frequency analysis of the RV time series using both the Generalized Lomb-Scargle periodogram (GLS; Zechmeister and Kürster, 2009) and the Iterative Sine-Wave method (ISW; Vaniček, 1971). The most prominent feature in the top panel of Fig. 3.8 is a long-term trend. Since it is unconstrained by the time span of the observations, its value is practically 0.0 d^{-1} and the peak structure is very similar to the spectral window (insert in the top panel). The alias structure centered

at the orbital frequency $f=1.40 \text{ d}^{-1}$ due to the planet is already discernible in the first power spectrum. We tried to add both a linear and a quadratic term in the frequency analysis to describe the trend. A linear term leaves residual power close to 0.0 d^{-1} , evidence of an unsatisfactory fit, while the orbital frequency becomes very evident when a quadratic term is introduced (bottom panel).

Even if we performed more than one measurement per night, the time separation was not very large due to the high number of nights with the star visible only in the second half of the night. This did not allow the effective damping of the $\pm 1 \text{ d}^{-1}$ aliases, that are as high as the true peak.

3.2.2.1. Studying the Star, Knowing the Planet: Stellar Parameters using Spectroscopy

Stellar activity is dependent on stellar type, mass, and stellar age. The stellar mass and radius, in turn, depend on precise atmospheric stellar properties measurements, so it is extremely important to obtain the effective temperature, surface gravity, and the metallicity of the star.

Furthermore, observational and theoretical works have shown that the processes of planet formation and evolution seem to depend on stellar properties (e.g., Udry and Santos, 2007b; Mayor et al., 2011b; Mortier et al., 2013; Adibekyan et al., 2013). Homogeneously deriving precise stellar parameters makes possible to look for correlations between the various parameters and statistically evaluate them, allowing us to check these theories.

We adopted three different methods to determine HD 80653 stellar atmospheric parameters. The first method, *CCFpams*¹, is based on the determination of several cross-correlation functions (CCFs) obtained by including spectral features with different sensitivity to the photospheric parameters. This technique uses the stellar parameters of high signal-to-noise (SNR), high-resolution HARPS-N spectra of FGK Main Sequence stars for the empirical calibration of stellar temperature, metallicity and gravity on the equivalent width of CCFs obtained with selected subsets of stellar lines, according to their sensitivity to temperature.

The second approach, *ARES+MOOG*, is based on the measurement of the equivalent widths of a set of iron lines. Once we obtained the iron abundances from the equivalent widths of the set, the technique derives temperature and microturbulent velocity by minimizing their trend with respect to excitation potential and reduced equivalent width respectively, while the gravity is obtained by imposing the same

¹<https://github.com/LucaMalavolta/CCFpams>

Method	T_{eff} [K]	$\log g$ [cgs]	[Fe/H] [dex]	$v \sin i$ [km s ⁻¹]
ARES+MOOG	6022±72	4.36±0.12	0.25±0.05	
CCFpams	5947±33	4.41±0.06	0.30±0.03	
SPC	5896±50	4.35±0.10	0.26±0.08	3.5±0.5

Tab. 3.1.: HD 80653 atmospheric parameters. ARES+MOOG errors are inflated for systematics, while CCFpams and SPC errors are only internal.

average abundance from neutral and ionized iron lines (see Sousa, 2014, and references therein for more details). We coadded all HARPS-N spectra for this analysis. Equivalent widths measurements automatically carried out using ARESv2 (Sousa et al., 2015). The linelist comprises of roughly 300 neutral and ionised iron lines (Sousa et al., 2011). We performed line analysis and spectral synthesis using a grid of ATLAS plane-parallel model atmospheres (Kurucz, 1993), the 2017 version of the MOOG code² (Snedden, 1973), and assuming local thermodynamic equilibrium. We then determined the atmospheric parameters by imposing excitation and ionisation balance and, following the recipe from Mortier et al. (2014), we corrected the surface gravity based on the effective temperature to obtain a more accurate value. Systematic errors were added quadratically to our internal errors (Sousa et al., 2011).

The third method we used, the Stellar Parameters Classification tool (SPC, Buchhave et al., 2014) performs a cross-correlation of the individual RV-shifted observed spectra with a library of synthetic spectra and then interpolates the resulting correlation peaks to determine the best-matching atmospheric parameters. As SPC is a spectral synthesis method, it also allows to determine the projected rotational velocity $v \sin i$ of HD 80653 and it was shown by Torres et al. (2012) that it is a very reliable tool for low rotational velocities.

The stellar parameters determined with the three methods show general agreement and the results are reported in Table 3.1.

3.2.2.2. Mass and Radius

The stellar mass and radius are very difficult to measure directly. If a star has a known distance either from parallax or from membership in a cluster it is possible to determine its effective temperature and luminosity from observations. Then stellar evolution models can be used to approximate the star’s mass and radius.

²<http://www.as.utexas.edu/~chris/moog.html>

We adopted the apparent B and V magnitudes photometry from the Two Micron All Sky Survey (2MASS; Cutri et al., 2003; Skrutskie et al., 2006) and the Wide-field Infrared Survey Explorer (WISE; Wright et al., 2010) (see Table 3.2. The distance value we used is listed in Table 3.2 and is derived from the intermediate of three values given by the Gaia DR2 parallax (Gaia Collaboration et al., 2016; Gaia Collaboration et al., 2018), corrected for a systematic bias (Stassun and Torres, 2018) and for the nonlinearity of the parallax-distance transformation and the asymmetry of the probability distribution (Bailer-Jones et al., 2018). Using the atmospheric parameters from Table 3.1 and assuming $\sigma_{T_{\text{eff}}} = 70$ K, $\sigma_{\log g} = 0.12$ dex and $\sigma_{[\text{Fe}/\text{H}]} = 0.08$ dex as realistic errors for all our parameter estimates, based on the combination of the expected systematic errors (e.g., Sousa et al., 2011) and the most conservative internal error estimate for each parameter from all the techniques, we determined the stellar mass and radius by fitting stellar isochrones. We used the code `isochrones` (Morton, 2015) fitting for two different evolutionary models: the MESA isochrones and Stellar Tracks (MIST; Paxton et al., 2011; Choi et al., 2016; Dotter, 2016) and the Dartmouth Stellar Evolution Database (Dotter et al., 2008). We ran a fit for each set of stellar atmospheric parameters and repeated the analysis for each set of stellar evolutionary models, for a total of six different fits.

As a final step, we joined the six posterior distributions from the individual fits and calculated the median and 16th and 84th percentile of the combined posterior distribution (e.g., Rice et al., 2019). We obtained consistent values within errors and concluded that HD 80653 has a mass $M_{\star} = 1.18 \pm 0.04 M_{\odot}$, a radius of $R_{\star} = 1.22 \pm 0.01 R_{\odot}$ and an age of 2.7 ± 1.2 Gyr (Table 3.3).

3.2.2.3. Studying the Star, Knowing the Planet: Analyzing Stellar Activity using Spectroscopy

We investigated the periodicities in the spectroscopic time series of the RV data by including the long-term trend and the orbital frequency as known constituents and those of the main activity indicators FWHM, BIS, and S_{MW} . We immediately noted in Fig. 3.9 that there is not any clear peak suggesting other planetary signals and that none of the periodograms of the indicators show a peak at the frequency $f = 1.40 \text{ d}^{-1}$ detected in the RV data, definitely supporting its full identification as the orbital frequency of HD 80653 b.

On the other hand, these periodograms show some peaks in the frequency range where we found signals in the K2 photometry, namely, $0.03\text{-}0.06 \text{ d}^{-1}$ (the grey region). In particular, the S_{MW} data and the RV residuals show peaks above

EPIC 251279430		
HD 80653		
2-MASS J09212142+1422046		
<i>Parameter</i>	<i>Unit</i>	<i>Value</i>
RA (J2000)	[hms]	09:21:21.42
Dec(J2000)	[dms]	14:22:04.52
B	[mag]	10.118 ± 0.031
V	[mag]	9.452 ± 0.023
<i>Kepler</i>	[mag]	9.45
J	[mag]	8.315 ± 0.023
H	[mag]	8.079 ± 0.029
K	[mag]	8.018 ± 0.021
W1	[mag]	7.959 ± 0.024
W2	[mag]	8.000 ± 0.020
W3	[mag]	8.011 ± 0.021
W4	[mag]	7.869 ± 0.204
Distance	[pc]	109.86 ± 0.81

Tab. 3.2.: Known stellar parameters of HD 80653.

Parameter	Unit	Value
$\log g$	[cgs]	4.34 ± 0.02
$M_{\star}$	[$M_{\odot}$]	1.18 ± 0.04
$R_{\star}$	[$R_{\odot}$]	1.22 ± 0.01
Age t	[Gyr]	2.67 ± 1.20
$\log(L_{\star}/L_{\odot})$		0.24 ± 0.02
$\rho_{\star}$	[$\rho_{\odot}$]	0.64 ± 0.04

Tab. 3.3.: HD 80653 stellar parameters from isochrone fits as obtained from the joined posteriors of six individual fits. It is very interesting to note the excellent agreement between *Gaia* and spectroscopic values of $\log g$ listed in Table 3.1.

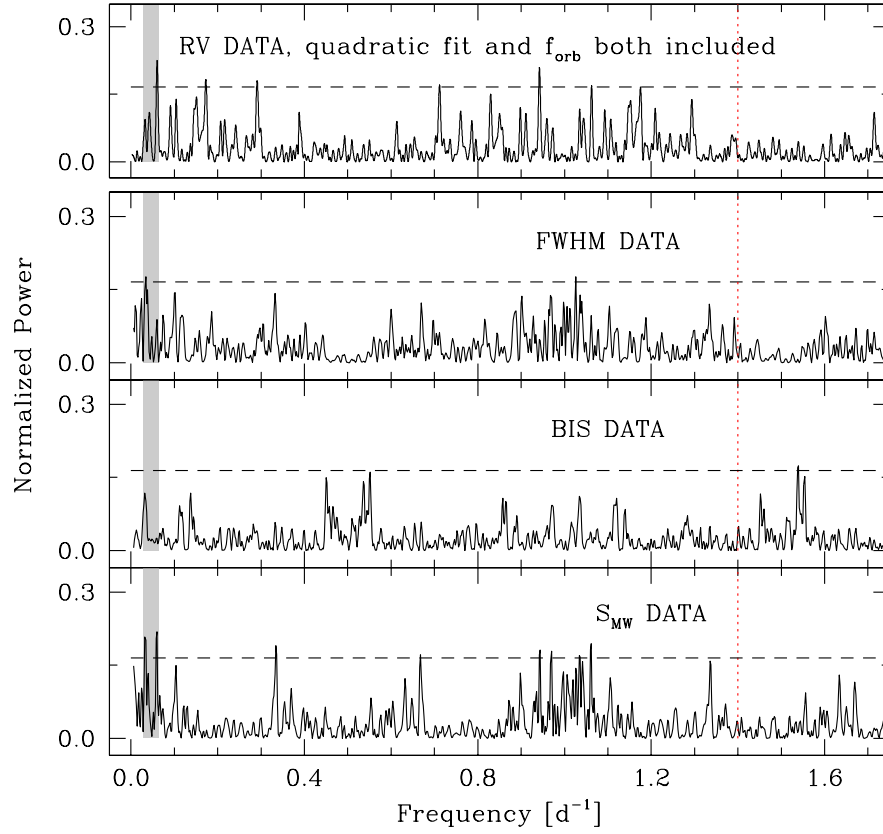


Fig. 3.9.: *Top to bottom:* ISW power spectra of the RV (long-term trend and orbital frequency considered as known constituents), FWHM, BIS, S_{MW} (no known constituent) time series. The vertical red line indicates the orbital period of the transiting planet. The grey region at low frequencies delimits the interval where the rotational frequency is expected from the *K2* photometry. The horizontal lines mark the 1% FAP.

the false alarm probability³ (FAP) FAP=1% threshold at $f=0.060 \text{ d}^{-1}$, that is, $P=16.6 \text{ d}$. Therefore K2 photometry, $v \sin i$ measurement, and activity indicators all suggest a stellar rotation period in the range 16-20 d.

3.2.3 HARPS-N Spectroscopy: Radial Velocity Analysis for Planet Characterization

Radial velocities monitoring remains important for two main reasons when conducting the follow-up of a transiting planet: to confirm that a transit-like signal is indeed caused by a planet, and is not a false positive and to measure the planet's mass. Constraining the mass allows for a measure of the bulk density of the planets. Such measurements are difficult to make for small planets due to the small radial velocity signal such planets induce on the host stars, but are important to help understand their internal composition.

A good knowledge of these properties is essential for understanding the different kinds of planets and their distributions in our Galaxy. After studying in detail the star and its characteristics, we became able to obtain the three key ingredients to estimate planetary bulk composition of HD 80653 b.

Radial velocity measurements are difficult to make for small planets due to the small signal such planets induce on the host stars, but are important to help understand their internal composition. However, USP planets observations have some practical advantages. Thanks to their short period, they are easier to detect and their physical parameters are easier to measure. This allowed us to collect several spectra per night on several nights and use those spectra to model stellar activity with two different, complementary techniques for an accurate determination of the planetary mass.

The analyses were performed assuming circular orbits, an assumption mainly based on the extremely short circularization time for such a close-in planet (Matsumura et al., 2008).

When the periodicity of the stellar activity is well separated from the orbital period of the planet, as in our case, it is possible to assume that the RV variation due to the activity and that from an eventual outer planet, are constant within an orbital period of the USP planet. The nightly visibility window of our target was shorter than the orbital period of the planet, so we modeled the planetary signal fitting for nightly offset values calculated every two orbital periods, using the formula

³Calculated implementing the approximation proposed by Baluev (2008), which employs extreme value statistics to compute an upper bound of the false alarm probability for the alias-free case.

$$RV = K \sin\left(\frac{2\pi}{P}x(t)\right) + \sum_{i=0}^N B_i \Theta(t - t_0 - 2iP) \quad (3.4)$$

where P is the orbital period determined from the light curve, $\Theta(t)$ is the Heaviside step function, t_0 is the time of the first HARPS-N RV measurement, N is the number of nightly offsets, and $x(t)$ is the phase-folded mid-exposure time. We found the best-fit parameters via simple likelihood estimate, and then fed an MCMC technique (as implemented in python by emcee; Foreman-Mackey et al., 2013) with the output to determine appropriate errors on the RV amplitude and RV offsets, K and $\{B_i\}$ respectively, while held P and T_c constant as they were determined from the photometric analysis. We used 700 walkers initially placed in a small sphere (or Gaussian ball) around the values of the Maximum Likelihood Estimate parameters, running for 600 steps, of which the first 50 were discarded as burn-in phase. We then marginalized over all B_i s to obtain the posterior distribution for K , obtaining the errors on the RV amplitude from the width of this distribution. The resulting RV semi-amplitude due to planet b is $K = 3.46 \pm 0.27 \text{ m s}^{-1}$, corresponding to a mass $M_b = 5.5 \pm 0.5 M_\oplus$. The density of the planet is then $\rho_b = 7.2 \pm 1.1 \text{ g cm}^{-3}$.

The second approach used PyORBIT code to simultaneously model an orbit for the planetary signal and a polynomial to account for the trend in the RV data (Fig. 3.7), imposing Gaussian priors based on the light-curve fit on P_{orb} and T_c (Sect. 3.2.1.2. A first attempt at fitting the data without any modelling of the stellar activity resulted in a RV jitter of $2.9 \pm 0.3 \text{ m s}^{-1}$, clearly indicating the presence of an additional signal in the data. We then performed a combined analysis of RVs and activity indices using the Gaussian Process (GP) framework, trained on both the S_{MW} index and FWHM, the indicators that show hints of rotational modulation (see 3.2.2.3). PyORBIT runs the `george` library (Ambikasaran et al., 2015) to implement the mathematical definition of the kernel given by Grunblatt et al. (2015). We used a quasi-periodic kernel with independent amplitudes of covariance function h for each dataset to model RVs and the activity indicators, taking as common parameters the rotational period P_{rot} , coherence scale w , and decay timescale of activity regions λ . As suggested by López-Morales et al. (2016) we constrained w to a Gaussian prior $\mathcal{G}(0.35, 0.03)$, taking care to recompute the proposed prior of $\mathcal{G}(0.50, 0.05)$ to take into account the different coefficients in the kernel definition, while we used non-informative, uniform priors with broad intervals for all the other parameters. Again, we performed the posterior sampling using emcee, running the sampler for 50000 steps, discarding the first 15000 steps as a conservative burn-in.

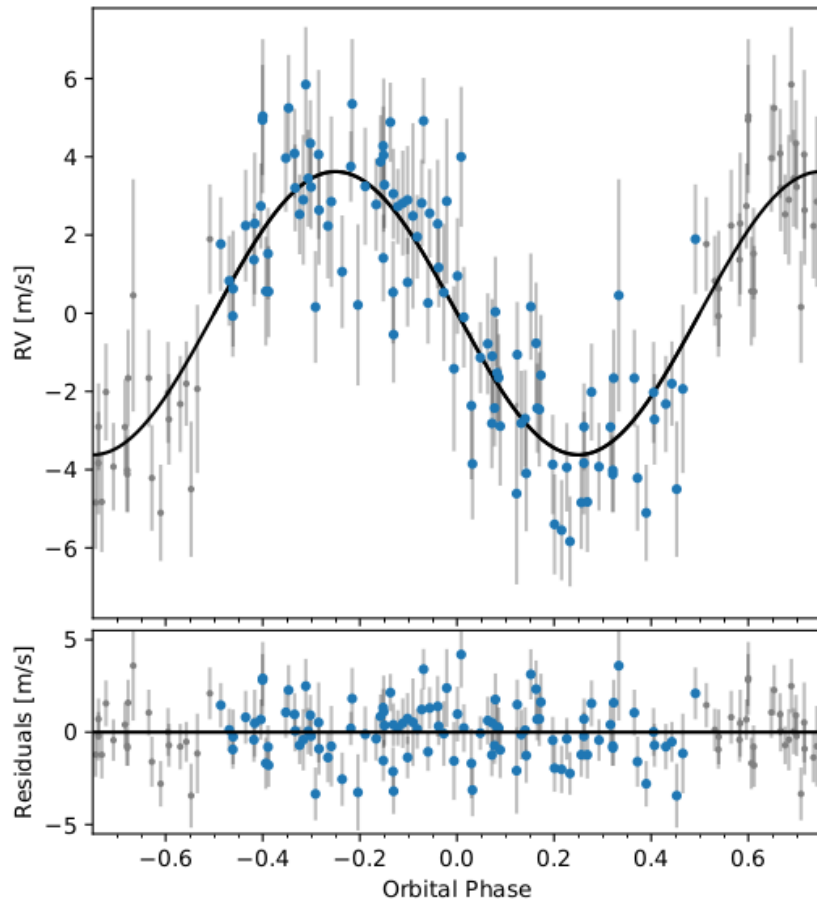


Fig. 3.10.: *Top panel:* phase-folded RV fit obtained using PyORBIT. Activity jitter and long-term trend were both removed. Larger blue dots delimitate the RV variation over a single orbital cycle. *Bottom panel:* residuals from the best fit.

The results obtained from the GPs trained firstly on the S_{MW} indicator and then on the FWHM one are very consistent. Both match very well the photometric determination of the rotational period, namely, $P_{\text{rot}}=19.2$ d. It is important to emphasize that the posterior distributions of the planet’s parameters were not affected by the exact choices for the GP regression and this is demonstrated indeed repeating the analysis using the RV data alone. The results obtained again are similar, but the errors are larger.

The GP analysis yielded an RV semi-amplitude of $K = 3.55 \pm 0.26 \text{ m s}^{-1}$ for the planet b, corresponding to a mass $M_b = 5.60 \pm 0.43 M_{\oplus}$ after taking into account the error on the period, stellar mass and the orbital inclination. For sake of completeness, we performed the PyORBIT analysis not assuming a circular orbit and the process returned an eccentricity value consistent with zero and parameters all consistent with the circular case.

The two methods used to model the RVs yield consistent results on the RV semi-amplitude and planetary mass, but we chose the parameters obtained with PyORBIT to continue our analysis. The resulting RV values with the best-fit model are shown in Fig. 3.10 and all the parameters for the analysis of the system are listed in Table 3.4.

The long-term trend seen in the RV plot only (Fig. 3.7) is an intriguing result. It strongly suggests an additional Keplerian motion, since long-term activity cycles do not show analogues in the specific indicators and HARPS-N has a proven long-term instrumental stability. The steady increase ($\dot{\gamma}=0.17 \text{ m s}^{-1}\text{d}^{-1}$) spans about 150 days. Winn et al. (2009) showed that there is a relation between $\dot{\gamma}$ and some properties of the companion:

$$\frac{m_c \sin i_c}{a_c^2} \sim \frac{\dot{\gamma}}{G} = (0.37 \pm 0.08) M_{\text{Jup}} AU^{-2} \quad (3.5)$$

where m_c is the companion mass, i_c its orbital inclination relative to the line of sight, and a_c its orbital distance. Assuming $i \simeq 90^\circ$, a substellar companion of $15 M_{\text{Jup}}$ would orbit at 6.4 AU, with a period of 5500 d. The last RV measurements in the dataset used for Frustagli et al. (2020) seemed to suggest a possible curvature. In such a case, and assuming a moderate eccentricity, we estimated a period in the range 260–400 d and a RV amplitude $2K_c \simeq 25 \text{ m s}^{-1}$. Under these hypothetical conditions, we tentatively suggested a mass of 0.35–0.50 M_{Jup} for the companion.

Furthermore, given that HD 80653 is bright, and in proximity of the Sun, intermediate-separation giant planetary and brown dwarf companions are likely to be detectable using Gaia (e.g., Sozzetti and de Bruijne, 2018, and references therein). Therefore,

<i>Fitted parameters</i>	
Transit epoch T_c [BJD _{TDB}]	2458134.4244 ± 0.0007
Prior $\mathcal{U}$ [2458134.324, 24588134.524]	
Orbital Period P_b [d]	0.719573 ± 0.000021
Prior $\mathcal{U}$ [0.6195124, 0.8195124]	
<i>Light curve</i>	
LC jitter (normalized flux)	0.000055 ± 0.000001
Prior $\mathcal{U}$ [0.000, 0.002]	
Kepler limb-darkening coefficient q_1	$0.31^{+0.35}_{-0.19}$
Prior $\mathcal{U}$ [0.000, 1.000]	
Kepler limb-darkening coefficient q_2	$0.40^{+0.33}_{-0.26}$
Prior $\mathcal{U}$ [0.000, 1.000]	
Stellar density $\rho_\star$ [$\rho_\odot$]	0.64 ± 0.04
Prior $\mathcal{G}$ [0.64, 0.04]	
Radius ratio $R_p/R_\star$	0.0121 ± 0.0004
Prior $\mathcal{U}$ [0.000010, 0.500000]	
Impact parameter b	$0.40^{+0.08}_{-0.14}$
Prior $\mathcal{U}$ [0.000, 1.000]	
<i>Radial velocities</i>	
RV jitter [m s^{-1}]	$0.62^{+0.34}_{-0.35}$
Prior $\mathcal{U}$ [0.009, 297]	
Systemic RV γ [m s^{-1}]	8310.17 ± 2.2
Prior $\mathcal{U}$ [7291.19, 8429.05]	
Linear term $\dot{\gamma}$ [$\text{m s}^{-1} \text{d}^{-1}$]	0.17 ± 0.03
Prior $\mathcal{U}$ [-1, +1]	
Radial-velocity semi-amplitude K [m s^{-1}]	3.55 ± 0.26
Prior $\mathcal{U}$ in $\log_2$ [-6.64, 9.97]	
Rotational period of the star P_{rot} [d]	19.8 ± 0.5
Prior $\mathcal{U}$ [5, 40]	
Coherence scale w	0.340 ± 0.034
Prior $\mathcal{G}$ [0.350, 0.035]	
Decay timescale of activity regions λ [d]	$22.5^{+5.9}_{-4.7}$
Prior $\mathcal{U}$ [5, 500]	
Amplitude of GP h	$5.00^{+1.22}_{-0.87}$
Prior $\mathcal{U}$ [0.01, 100]	
<i>Derived parameters</i>	
Kepler limb-darkening coefficient u_1	$0.41^{+0.34}_{-0.25}$
Kepler limb-darkening coefficient u_2	$0.10^{+0.39}_{-0.30}$
Transit duration T_{14} [d]	$0.0749^{+0.0027}_{-0.0025}$
Inclination i [deg]	82.1 ± 2.4
Scaled semi-major axis $a/R_\star$	2.92 ± 0.05
Orbital semi-major axis a [AU]	0.0166 ± 0.0003
Planet mass M_b [$M_\oplus$]	5.60 ± 0.43
Planet radius R_b [$R_\oplus$]	1.613 ± 0.071
Planet density ρ_b [g cm^{-3}]	7.4 ± 1.1

Tab. 3.4.: HD 80653 system parameters published in (Frustagli et al., 2020).

additional, independent constraint on the orbital architecture of the HD 80653 planetary system might be allowed from the third major Gaia Data Release, giving us the chance to further characterize this interesting planetary system.

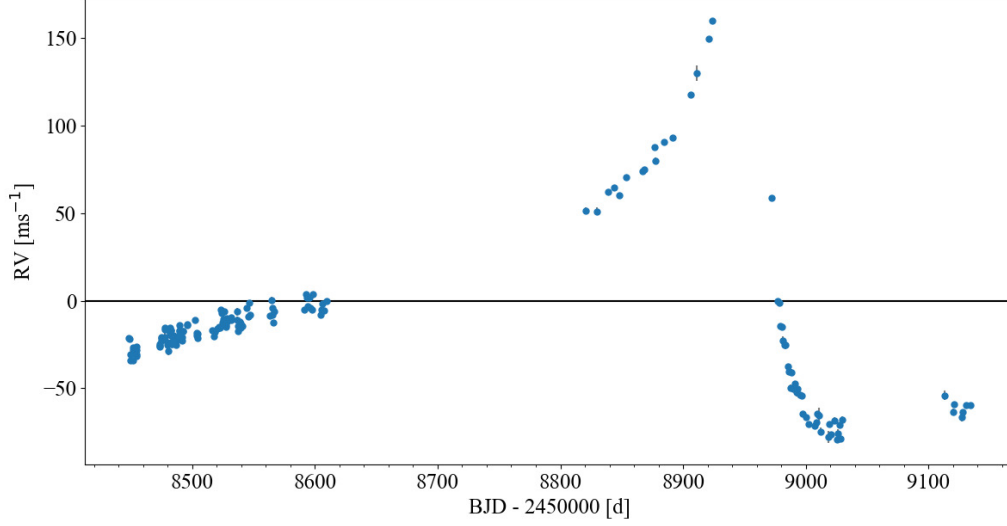


Fig. 3.11.: Radial velocities time series extracted from HARPS-N spectra updated to November 2020.

3.2.4 HD 80653 System: One Year Later

The continued RV monitoring of the system, significantly extending the time baseline, enabled us to tighten the constraints on the orbital parameters and mass of the second planet, thereby allowing investigations of its role in the formation of the USP super-Earth HD 80653 b. The observations are currently ongoing and the new data already suggest that the companion could have a longer period and a higher mass than previously expected. The new velocities have been obtained between November 2019 and November 2020. Figure 3.11 shows the RV time series extracted from HARPS-N spectra, for a total of 169 spectra with S/N in the range 40–127 at 550 nm. The long term trend observed previously turned out to be the signal of an highly eccentric and massive companion. Using PyORBIT as described in Section 3.2.3, I performed the posterior sampling using emcee, running the sampler for 50000 steps, discarding the first 15000 steps as a conservative burn-in. The preliminary analysis with a two planets model shows interesting results for the second object of the system.

The analysis yielded an RV semi-amplitude of $K = 173.93^{+12.31}_{-10.37} \text{ ms}^{-1}$ for the planet c, corresponding to a mass limit $M_c \sin i_c = 5.16^{+0.24}_{-0.22} M_J$ after taking into account the error on the period, stellar mass and the orbital inclination. Table 3.5 reports the parameters for the second planet of the system and the RV values with the best-fit model are shown in Fig. 3.12, an analysis that will be refined for being published in a second paper (Frustagli et al., in prep.). The orbital parameters of the two planets will be further investigated in the paper, with a particular focus on

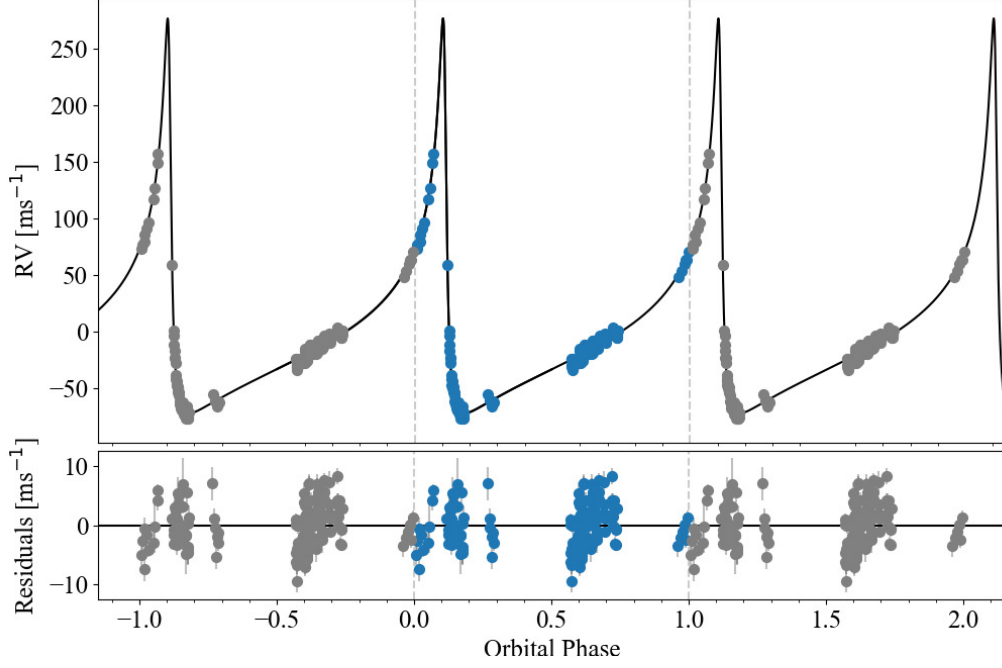


Fig. 3.12.: *Top panel:* phase-folded RV fit for the planet c obtained using PyORBIT. Larger blue dots delimitate the RV variation over a single orbital cycle. *Bottom panel:* residuals from the best fit. The orbital period of the companion results to be $P_c = 956.39^{+20.80}_{-19.62}$ d, with a high eccentricity $e = 0.836 \pm 0.011$.

eccentricity and mutual inclination, in the attempt to understand what influence the outer planet had on the formation and evolution of the inner USP, and vice versa. In particular, we expect that during the early evolution of multi-planetary systems

<i>Second planet parameters</i>	
Orbital Period P_c [d]	$956.39^{+20.81}_{-19.62}$
Radial-velocity semi-amplitude K [m s^{-1}]	$173.93^{+12.31}_{-10.37}$
Scaled semi-major axis $a/R_\star$	353.65 ± 7.04
Orbital semi-major axis a [AU]	2.009 ± 0.036
Planet mass M_c [M_{Jup}]	$5.16^{+0.24}_{-0.21}$
Planet radius R_c [R_{Jup}]	Unknown
Eccentricity e_c	0.855 ± 0.015
$\sqrt{e_c} \cos \omega_c$	$0.685^{+0.038}_{-0.036}$
$\sqrt{e_c} \sin \omega_c$	$0.620^{+0.027}_{-0.031}$
Argument of periastron ω_c [rad]	$0.735^{+0.048}_{-0.052}$

Tab. 3.5.: HD 80653 c parameters.

the inner planet becomes a USP and shows a low misalignment with respect to the stellar spin-axis, while its exterior companion remains inclined. The two planets are therefore expected to exhibit a large mutual inclination. Being able to infer this type of inclination in HD 80653 system, could help the future theoretical studies

related to the formation of USP planets, helping to disentangle from the different formation scenarios that have been proposed in literature (e.g. Petrovich et al., 2019; Pu and Lai, 2019).

3.2.5 Discussion

A combined analysis of HARPS-N high-resolution spectroscopy and K2 photometry allowed us to determine the HD 80653 system parameters and, in particular, revealed that this planet has an orbital period $P_b = 0.719573 \pm 0.000021$ d, a radius $R_b = 1.613 \pm 0.071 R_\oplus$, and a mass $M_b = 5.60 \pm 0.43 M_\oplus$, leading to a density $\rho_b = 7.4 \pm 1.1 \text{ g cm}^{-3}$.

HD 80653 b has a bulk density consistent, within uncertainties, with that of an Earth-like rocky composition (32.5% Fe/Ni- metal + 67.5% Mg-silicates-rock) and the uncertainty in our mass determination is small enough that our density estimate excludes the presence of any significant envelope of volatiles or H/He on the surface of the planet. Owing to its proximity to the host star and the fact that the host star is brighter than our own Sun, this planet receives very high bolometric irradiation. Thus, its equilibrium surface temperature for null albedo and uniform redistribution T_{unif} of heat to the night-side is on the order of 2500 K, enough to completely melt most silicates-rocky materials as well as iron and its alloys under 1-bar surface pressure. This planet is then expected to be a lava-ocean world, especially at the substellar point facing the star, but as pointed out in Section 3.2.1.3 this prediction seems at odds with the non-negligible night-side emission estimated by the secondary eclipse analysis. Infrared observations with the forthcoming James Webb Space Telescope could help to refine the Bond albedo and thus constrain the geometric albedo of the planet, unveiling the true nature of HD 80653 b.

Moreover, a refined analysis could help to better understand the process by which HD 80653 b formed. It is unlikely that such an USP planet could form in situ, because a simple equilibrium condensation calculation shows that Magnesium-Silicates, one of the major chemical components of rocks, would only condense out of the nebula from gas phase into solid phase below around 1400 K (Lewis, 2004). It is more likely that it initially formed on a wider orbit and was subsequently transported to its current proximity to the star through migration.

In such a scenario the unseen companion could play a relevant role. Theoretical calculations by Petrovich et al. (2019) show that planetary systems can be transformed by secular chaos, a process that can induce large eccentricity and inclinations variations by non-linear secular interactions. Such a mechanism could be a scaled-down version

of one of the mechanisms proposed for hot Jupiter formation, but only discoveries from other instruments like TESS along with follow-up studies of systems with USP planets could help to reveal whether secular chaos is a prevalent process in shaping the dynamical properties this type of planets.

3.3 Conclusions: From Discovery to Characterization

In this section I draw a few main conclusions about the work presented in this chapter. As the number of exoplanets known is growing, we understand that the characterization of these planets and their host stars is extremely important to put constraints on the formation of the systems observed. Thanks to this experience with the HARPS-N GTO Collaboration I had the opportunity to interact with many scientists from different countries and learn new methods for analyzing spectroscopic and photometric data.

My involvement in this team helped me to enhance my expertise in the field of exoplanet characterization, guiding the analysis of a planet and the preparation of a paper for a peer-reviewed journal and contributing to the selection of targets to maintain the Collaboration competitive in the near future. HD 80653 b is an interesting object that will help the community to unveil the nature of the mysterious sub-population of exoplanets represented by USP planets. The work undertaken on this target has highlighted into my mind the complexity inherent to detailed characterization in the presence of stellar activity and the analyses needed to get to know both the radius and the mass of an exoplanet. The uncertainties on these planet parameters need to be small in order to test the physics used in the planet evolution models, and to discriminate between different structures and compositions that can be inferred from the bulk planetary density. The Kepler/K2 dataset is often ill-suited for characterization purposes, because many of the planets observed orbit distant and thus faint stars. However, new generation missions (e.g., TESS) are currently proving their effectiveness, mapping the entire sky and helping to discover short-period transiting planets around brighter stars. In the mid 2020s, the PLATO mission will provide high quality photometry and this will allow similar measurements to be done for longer period planets. The efforts to estimate the masses of these planets, which in turn are required to determine the bulk density of planets and to infer their composition, are as much complex as important. Combining these studies with the analysis of the planetary atmospheres will give us important insights in chemical and eventually even biological processes.

As new facilities and new data become available, the experience gained in this collaboration will allow me to be ready for the challenges to come.

GAPS Search for Young Exoplanets

While there is a great deal of excitement and effort in the hopes of finding terrestrial sized exoplanets, another realm of exoplanet discovery that is often overlooked is that of ones of differing ages to explore how planetary systems can evolve. Stars younger than about 100 million years tend to be unruly. They are prone to flares and other eccentric behaviors that often make observations messy. Additionally, many young stars often retain debris disks or are still embedded in the nebula in which they formed which also obscures observations. The environmental conditions, such as disk properties, multiplicity, and stellar radiation fields have a strong influence on the processes that regulate the observed planetary properties (e.g., orbital architecture, internal structure, and atmospheric composition). Currently, our planet formation paradigm is largely inferred from models based on data from billion year old systems, and whether planetary systems reflect formative versus evolutionary processes is unknown. Knowledge of precisely when and at what distances from the parent star planets form, with what frequency they form, how rapidly they migrate or are disrupted and/or ejected, and at what age planetary systems acquire stable configurations is poor. Discovering young (e.g., < 1 Gyr) exoplanets will thus help to probe the main causes of planetary evolution, and help to fill a key gap in our knowledge of exoplanet history.

The combination of several factors such as increased activity, rotation rates and relative proximity to neighbouring stars (e.g., Briceno et al., 2018; Cegla et al., 2019) can result in periodic stellar variability similar to that produced by planetary signals in both period and intensity. Host stars of young exoplanets represent then significant challenges for discovery. Despite the difficulties in dealing with the identification of planetary signals in presence of the very high activity levels of their hosts, the detection of a small number of young exoplanets with radial velocity (RV) have been announced (e.g., Donati et al., 2016; Yu et al., 2017).

In spite of these obstacles, GAPS team is trying to exploit the capabilities of the HARPS-N and GIANO-B spectrographs, coupled with an optimized observing strategy to explore a still uncharted territory in the realm of planet formation and evolution. The GAPS Young Objects (YO) program objective is the study of

the origin of planetary systems shaped by the different stages of orbital evolution, through the determination of the architectures and orbital parameters of hot and warm Jupiters (HJ and WJ, hereafter) and hot Neptunes (HN) around young (≤ 50 Myr) and intermediate-age (600 – 700 Myr) stars.

A number of key phenomena produce observable tracers of the environmental conditions at the formation time, of the different degrees of subsequent dynamical evolution, and of the role played by the properties of the central stars. By investigating a significant sample of young objects and performing a reliable statistical analysis, the ultimate goal of this program is to be able to study the impact of these processes and shed a light on planet early formation and evolution.

4.1 YO Program Sample

The YO sample was carefully selected, in order to reach specific goals in exoplanetary architecture study. The expectation is to be able to confirm or disprove the significantly higher frequency of HJs at very young ages (Yu et al., 2017). In addition, the hope is to distinguish among the timescales of the HJ migration, by comparing the frequencies and properties of planets at the age of few Myr to those at a few hundreds Myr, and to those orbiting older stars. Depending on the level of magnetic activity, different regimes of planetary migration, as well as the possibility that a fraction of HNs evolved from partially evaporated HJs, by studying the presence of lower mass (HNs) and longer period (WJs) planets around the intermediate-age stars, can also be explored. The sensitivity to warm Jupiters nicely complements the detection parameter-space of NASA’s TESS satellite (Ricker et al., 2014), which is limited by the 27 days duration of the observation for a large fraction of the sky. This will ensure a better efficiency for the survey as opposed to a blind search. Furthermore, the knowledge of planetary radius from transits is critical for the physical characterization of the planet, providing additional diagnostics to disentangle the formation and migration path of close-in planets.

The sample is composed by about 40 young late F-G-K stars as a reasonable compromise between the scientific objective and the actual feasibility of a large program. High cadence observations over an individual season are planned for each target, a mandatory effort to disentangle correlated noise due to stellar activity from Keplerian signals. On average, the GAPS team obtain ~ 30 -40 spectra per target, with exposure times between 900 and 2400 sec.

In the following Sections, I will present the analysis of the target I studied for the GAPS Young Object program during the three years of my PhD.

4.2 Young Object 09: TYC 4610-1318-1

In this Section I present the RV measurements of the star TYC 4610-1318-1 (YO-09, hereafter), a member of the Cepheus open cluster (age ~ 10 Myr). It is a K1 star, with magnitudes $V=11.2$, $J=9.5$, $H=9.2$, $K=9.0$ (Cutri et al., 2003), and a rotational period of 5.6 days. It is also a star with a relatively low activity level, according to the chromospheric index $\log R_{\text{HK}} = -4.13$, calculated through the dedicated tool of the HARPS-N DRS with the method provided in Lovis et al. (2011), as implemented on YABI¹ workflow. We monitored this star between 2017 Jul 10 and 2020 Jan 17, in order to gather high resolution spectra. The dataset is composed

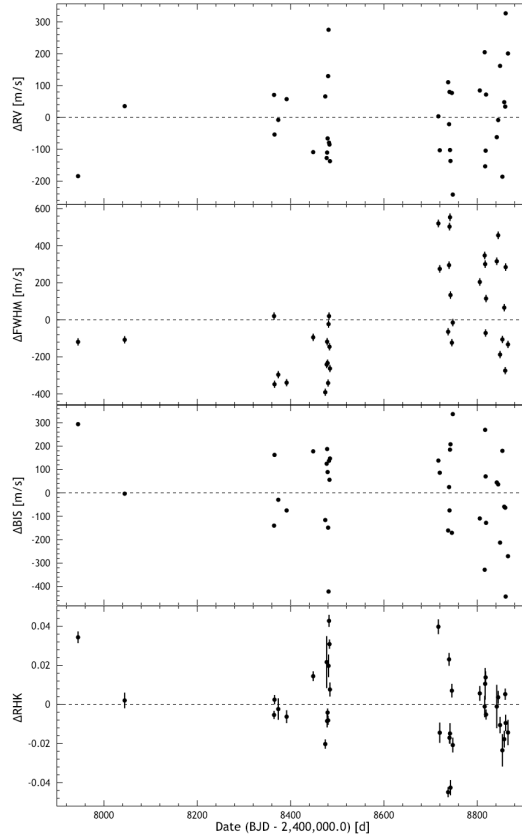


Fig. 4.1.: Radial velocities and stellar activity indicators time series extracted from HARPS-N spectra.

of 38 HARPS-N spectra. The HARPS-N RVs were obtained with the HARPS-N DRS, using the K5 mask template. All the spectra were taken with an exposure time of 2200 s. Two spectra with low signal-to-noise ratio (S/N) taken on two nights

¹YABI is a 3-tier application stack that allows accredited users to run HARPS-N and GIANO-B data reduction pipelines on private and public data from TNG archive.

were no longer considered. The 36 remaining spectra have S/N in the range 31–88 (median S/N = 59) at 550 nm. The time series of the RVs and activity indicators are shown in Fig 4.1. Error bars on the FWHM and BIS values have been taken as twice those of the RV ones (Santerne et al., 2018).

4.3 Stellar Activity

Although extremely efficient and otherwise accurate, the sole RV method for the discovery of new exoplanets is not always reliable, especially on a blind search. Several factors can influence the analysis of the target and it is necessary to disentangle between the presence of a planet and stellar activity. The analysis of the activity indicators offers a first step to understand the nature a periodic signal in the time series.

I performed a frequency analysis of the RV time series of YO-09 using the generalized Lomb-Scargle periodogram (GLS; Zechmeister and Kürster, 2009). The most immediately noticeable peak can be found at the frequency $f = 0.17 \text{ d}^{-1}$, that is a period of 5.85 days, very close to the known rotational period of the star (Fig. 4.2). The analysis of the periodicities in the spectroscopic time series of the main activity indicators FWHM, BIS, and $\log R_{\text{HK}}$ seems to agree. The BIS periodogram shows indeed a prominent peak at the same frequency, definitely supporting its full identification as a stellar signal. However, it is worth noting that none of the time series show peaks above the FAP=10% threshold.

Finally, I calculated the Spearman correlation coefficients for RV versus FWHM, BIS, and $\log R_{\text{HK}}$ by using weighted values. I obtained 0.0487, -0.9693, and -0.2240, respectively. The strongest correlation is between RV and BIS, as expected from the similarity in the power spectra discussed above.

As a last attempt, I detrended the BIS activity indicator from the RV time series. YO-09 still shows no significant signals in the RV time series, so it can be discarded as a star hosting a planet. The information gathered from the analysis of the time series tell us that no further observations are needed for this target.

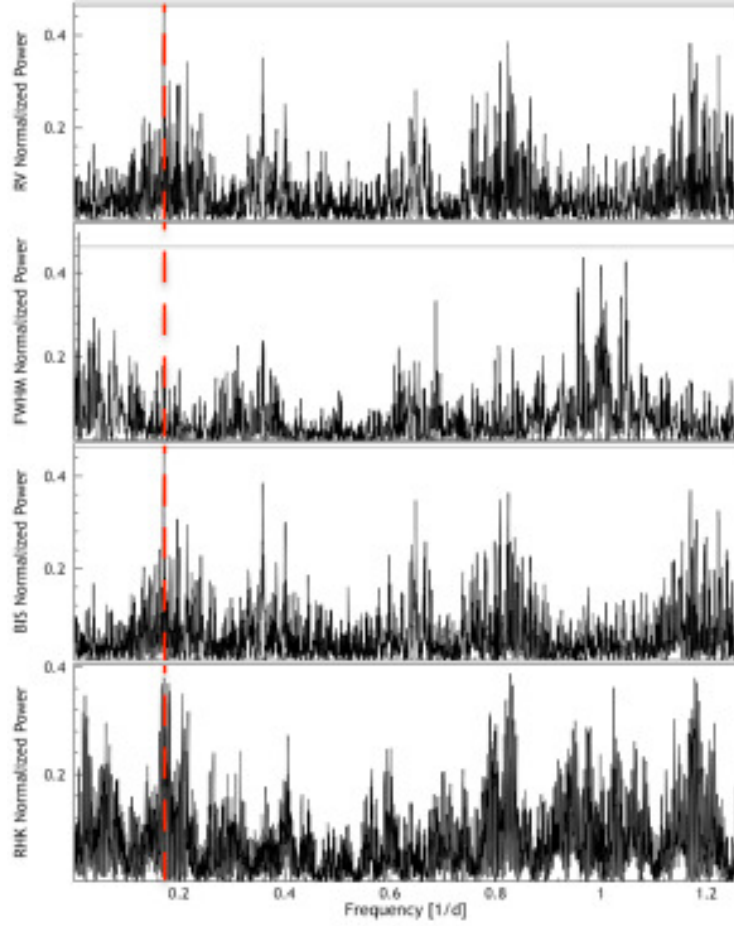


Fig. 4.2.: Power spectra of the RV, FWHM, BIS, $\log R_{\text{HK}}$ timeseries. The vertical red line indicates the rotational period of the star. The horizontal grey lines mark the 10% FAP.

4.4 Blind Search for a Periodic Signal

The blind intensive radial-velocity monitoring of a sample of young stars, to find new planets and to test the possible differences in the frequency of exoplanets with age is an ambitious and challenging task. The synergy of different techniques is very useful to allow the detection of periodic signals that can guide the discovery of a planet even in presence of an active star. The problem is that just a small fraction of exoplanets are transiting planets, therefore, despite the potentially strong limitation to the search for planets represented by high levels of magnetic activity seen at young ages, RV blind surveys are necessary to find and characterize new exoplanets.

Although the search for periodicities in the time series gave non-significant results, I

nevertheless attempted a blind search for a Keplerian signal in the radial velocities. I used `PyORBIT` in the attempt to find a possible planetary signal hidden in the RV time series. Since the analysis of the periodograms gave no hints on possible periods to use as a prior, I placed uninformative priors on all planetary parameters and tried two different approaches: a first attempt at fitting the data without any modelling of the stellar activity and a second one in which I performed a combined analysis of RVs and BIS activity index, the indicator with the strongest correlation with the RV data. In both cases I performed the posterior sampling using `emcee`, running the sampler for 50000 steps, discarding the first 15000 steps as a conservative burn-in. Both analyses resulted in a null detection of significant signals, with the conclusion that there is no strong evidence for a model with at least one planet. However, it must be highlighted that my results depend on the adoption of quite broad, uninformative priors for the planetary model parameters in all the analyses, as expected when conducting a blind search. A planet in this system cannot be completely excluded, but a high number of data could be needed to find a significant signal that could be attributed to the presence of a planet.

4.5 Conclusions

As a member of the GAPS team, I participated to the Young Objects program, guiding the analysis of the YO-09 target. The observations were used to detect possible planets around this young star and eventually estimate their orbital parameters and masses. The goal is analysing the observable tracers of dynamical evolution and understanding the origin of the observed diversity of planetary systems.

I used the knowledge gained through the study of HD 80653 b and applied it to this different target. Unfortunately, the eventual host planets cannot be seen with the available data and it was decided to discard this target as a potential candidate for the blind survey, therefore I was not able to go deeper into the analysis and study a young planet.

However, being involved into the YO project, I was able to collaborate to other works, such as, for example, Carleo et al. (2020). In this paper, we studied two targets: the Hyades star HD 285507 and the M dwarf AD Leo. We demonstrated the great potential of multiband high resolution spectroscopy, using data taken with the visible spectrograph HARPS-N and the NIR spectrograph GIANO-B. We confirmed the presence of a hot Jupiter around HD 285507 (Quinn et al., 2014). With our analysis, we refined the value of the orbital eccentricity, consistent with zero which, in principle, suggests that a type II migration mechanism could be responsible for

the current orbit of HD 285507 b. Tuomi et al. (2018) proposed the presence of a HJ around the very active star AD Leo. In this case, VIS and NIR RV observations do not agree, rejecting the Keplerian nature of the VIS RV variations and ascribing the observed modulation to stellar activity rather than a planetary companion. RV jitter due to the activity is reduced in the NIR with respect to the VIS range, due to the smaller contrast between stellar spots and the rest of the stellar disk (e.g., Crockett et al., 2012). For this reason, for very active stars, coupling different wavelength ranges is critical, in order to compare the corresponding results and disentangle the nature of the RV variations.

My involvement in the GAPS YO program helped me to better understand the difficulties in the blind search of exoplanets using the RV method. Stellar activity can be a real challenge and having as many information as possible about the star and its behaviour can be very useful to recognize the stellar origin of a signal. This was the case for YO-09 time series, in which the only signal I found was due to the rotation of the star. Taking advantage of the unique capabilities of the instruments available, such as HARPS-N and GIANO-B used in GIARPS mode, is mandatory to isolate the contribution by stellar activity and become able to recognize weak planetary signals. Such studies will shed a new light on our knowledge of exoplanets formation and evolution. The detection of planets at young ages is more challenging and being able to study this type of objects using and advanced technique such as multi-wavelength spectroscopy will be a critical skill in the next future, in order to utilize at best the next generation instruments.

Part II

Atmosphere Characterization

Exoplanetary Atmospheres

Thanks to the methods described in the previous chapter, exoplanets are now being discovered in profusion, making their study one of the fastest-growing subdisciplines in astronomy and planetary science.

The discovery of transiting exoplanets opened a new door for observing exoplanetary atmospheres. Starting with the first detections of atmospheric absorption (Charbonneau et al., 2002) and thermal emission from a transiting exoplanet (Charbonneau et al., 2005; Deming et al., 2005), atmospheric observations have been reported for more than fifty transiting exoplanets. These observations shall be added to the extended knowledge of exoplanets we gained in the last decades. These knowledges include macroscopic properties such as orbital parameters (eccentricities, separations, periods, spin-orbit inclination, etc.), bulk parameters (masses, radii, equilibrium temperatures), and properties of their host stars. The sum of these knowledges taught us that exoplanets are extremely diverse in all of their macroscopic physical parameters and strikingly different than the planets of our solar system.

We are now entering a new era where we can combine the data in order to understand the diversity of chemical compositions of exoplanets, their atmospheric processes, internal structures, and formation histories. The atmospheres of exoplanets can also host biosignature gases (e.g., Schwieterman et al., 2018), so the path to finding possible signs of life on exoplanets most likely leads through their atmospheres. Indeed, the atmosphere is a window into most of the exoplanetary properties. Moreover, exoplanetary atmospheres host a wide variety of physical processes, from intense infrared radiation and exotic chemistry to supersonic winds and electric currents. Measuring the ultraviolet (UV), optical, and infrared (IR) spectra of the atmospheres is one of the best ways to probe the nature of the alien worlds we are discovering.

State-of-the-art observations are now beginning to provide both the high sensitivity and long spectral baseline required to place detailed constraints on the various properties that allow us to characterize exoplanets.

In this Chapter, the current state of understanding exoplanetary atmospheres and the theoretical developments in our expectations for the habitability of terrestrial exoplanets will be briefly discussed. In the following Chapters the methods used to

characterize exoplanetary atmospheres will be depicted, with a particular attention on hot Jupiters and on the methods I developed to analyze the atmosphere of ultra-hot Jupiters, focusing on two different cases.

5.1 Exoplanet Atmospheres Models and Interpretation of the Observed Spectra

In parallel to the observational advances, the last decade has also seen substantial progress in the modeling of exoplanetary atmospheres and interpretation of exoplanetary spectra.

Models of exoplanetary atmospheres can vary over a wide range of physical conditions, computational complexity (1-D to 3-D models), and thermochemical conditions. However, before constructing a model, it is necessary to identify the parameters that should be taken into account. Some of them can be obtained in a straightforward way from observations, although there are some others for which we can just have guesses, albeit in some cases with great uncertainties.

The first step is then to understand which are these parameters and how we can infer the chemical composition of a planetary atmosphere from a reduced set of parameters related to the planet.

Gravity This parameter can be obtained directly from the mass and radius of the planet, which in turn can be derived from radial velocity and transit techniques, respectively. The stability of an atmosphere is largely related to its gravity and the X-ray and EUV flux of the host star. Moreover, depending on the gravity of the planet, light elements such as hydrogen and helium may or not escape from the planets, with strong implications for the elemental composition of the atmosphere. Gravity is also important because, together with the mean mass of particles μ and temperature T , it sets the scale height¹ of the atmosphere

$$H = \frac{kT}{\mu g} \quad (5.1)$$

where k is the Boltzmann constant.

¹Scale height is a parameter that tells us how compact or extended the atmosphere is. For example, using Earth's mean temperature ($T = 250K$), mean molecular weight ($\mu = 29$) and gravitational acceleration ($g = 9.8m/s^2$), Earth's height scale is $H_{\oplus} \cong 8.7km$. A hot Jupiter such as HD 209498b ($T = 1400K$, $\mu = 2.3$ and $g = 10m/s^2$) has a more extended atmosphere, with an height scale $H_{HD209498b} \cong 770km$

Elemental composition The relative abundances of the different elements is one fundamental aspect that determines the atmospheric composition, although it is rather difficult to infer these from observations.

According to the study of Solar System planets and on existing theories of planet formation (e.g., Goldreich et al., 2004; Chiang and Youdin, 2010; Morbidelli et al., 2012), the first difference between giant and terrestrial planets rises in the core formation. Giant planets are expected to form by core accretion, becoming massive enough to efficiently capture the nebular gas, and retain a thick H/He- dominated atmosphere. Terrestrial planets do not gain enough mass to efficiently accrete or retain H₂/He. Their atmospheres depend on their mass and evolutionary history and are expected to be dominated by secondary products such as H₂O, CO₂, CO, N₂, Ne, Ar, Kr, SO₂, SiO₂, outgassed from the solid planetesimals that formed the planets or supplied by later impacts by solid bodies.

It is important to note that in between these two great categories, there are super-Earths and sub-Neptunes whose elemental composition is unknown (e.g., Haghighipour, 2013; Marcy et al., 2014; Rogers, 2015). A comparison between the outcomes of models and observations, can help to put constraints on the elemental composition of the planetary atmosphere, which in turn provide clues to the formation and evolution of the planet itself.

Stellar flux The luminosity of the host star and the orbital distance, two properties that can be well constrained by observations, are essential to define the amount of energy received at the top of the atmosphere per unit time and unit area. The spectral type of the star has a great importance in affecting atmospheric characteristics. Depending on the energy of the incoming photons there will be different effects on the atmosphere. Visible and infrared photons are responsible of the heating of the atmosphere, especially at pressures greater than ~ 1 mbar (e.g., Seager and Sasselov, 1998; Barman et al., 2005; Burrows et al., 2006). Ultraviolet photons heat the high-altitude thermosphere, leading to ionization and dissociation of atmospheric constituents (e.g., Hu et al., 2012; Rimmer and Helling, 2016).

Internal heating The interiors of planets can provide a source of heat for the atmosphere. The internal heating can be estimated from theoretical models of the evolution of the planet interior (e.g., Guillot, 2005; Ogilvie, 2014). The problem is that, since the uncertainties in some key parameters (e.g. the bulk material of the planet interior and the age of the star) are great, internal heating is poorly constrained in most cases.

Thermal structure The vertical distribution of the atmospheric temperature can be retrieved from models. The atmospheric temperature has an enormous influence on the chemical composition because depending on whether the atmosphere is hot or cold, the major constituents and the type of condensates formed are completely different.

Strength of transport processes A variety of processes such as advection, diffusion and turbulent motion take place inside an atmosphere at different scales. The consequence is the transport and mixing of material between different regions. These processes are a source of disequilibrium because they can transport molecules that were originally formed in a given location to other atmospheric regions. In particular, the vertical chemical structure can be strongly affected by transport processes, but it is very difficult to obtain a realistic estimation of the strength of these processes.

The parameters described above are what we need to create a model of a planetary atmosphere that focuses on some particular aspects, adopting approximations for some other. These models aim at describing how the atmospheric constituents are distributed.

On the one hand, there are one-dimensional models that concentrate on solving the radiative transfer and thermal balance in the vertical direction. These are radiative-convective equilibrium models that make some assumptions about the chemical composition of the atmosphere, either adopting a particular one suitable for the modeled planet or assuming that chemical equilibrium holds in the atmosphere, and neglecting any fluid dynamics. For an assumed composition, in addition to the P-T profiles these numerical models also calculate the line-by-line thermal emission and reflectance spectra of the planetary atmospheres (Robinson and Catling, 2012; Parmentier and Guillot, 2014; Parmentier et al., 2015). Other type of models, the general circulation models (GCMs), are three-dimensional models which solve the Navier-Stokes equations and end up with a three-dimensional view of the circulation and thermal structure of the atmosphere. Some of the limitations of GCMs have to do with the approximations used to deal with the radiative transfer (e.g., Showman et al., 2009) and the chemical processes (Cooper and Showman, 2006). Hot Jupiters, hot Neptunes and super-Earths are the main targets of theoretical studies of exoplanet atmospheres. Due to the interest in the potential for life and its detectability outside of Earth, another popular topic is the theoretical characterization of habitable-zone planet. In the next Sections, the focus will be on the models of exoplanets atmospheres and the relation between theory and observations.

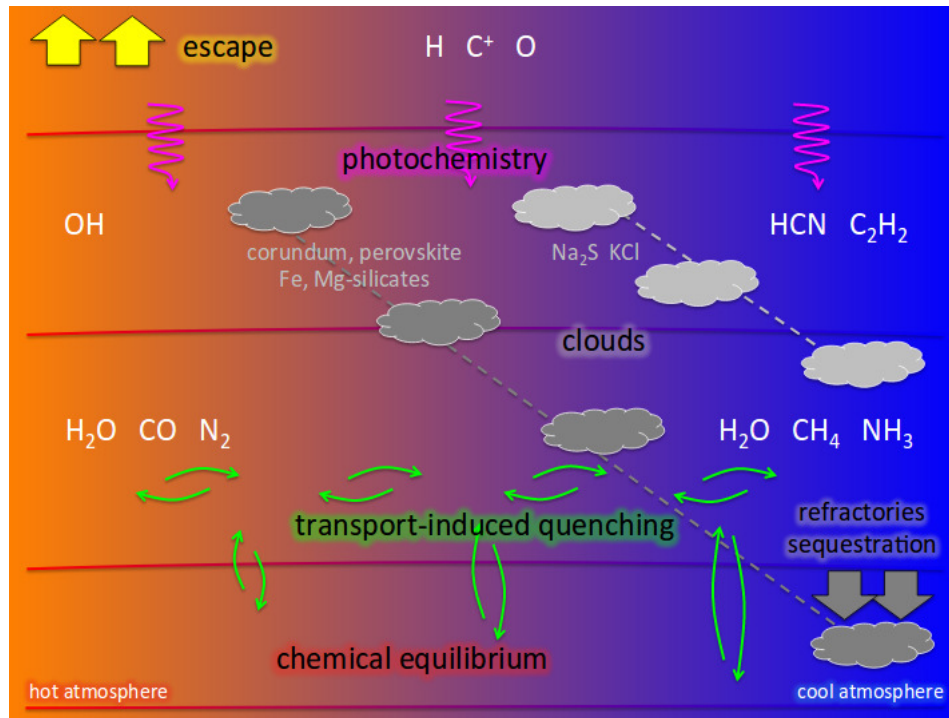


Fig. 5.1.: Sketch of the structure and processes at work in H/He-dominated atmospheres. The chemical composition in deep layers is controlled by chemical equilibrium, by transport-induced quenching in upper layers, and by photochemistry in still upper layers. Formation of clouds is an issue of increasing importance as the atmosphere becomes cooler. Escape can also be an important process in highly irradiated atmospheres (i.e., those with hot thermospheres), while sequestration of refractory elements becomes important in the cooler atmospheres. Image from Madhusudhan et al. (2016a)

5.2 Gas Giant Exoplanets Atmospheric Chemistry

According to their formation mechanism and to the bulk density inferred from observations, gas giant exoplanets are expected to have H/He-dominated atmospheres (Baraffe et al., 2010).

The chemical composition is controlled by chemical equilibrium in deep atmospheric layers, by transport-induced quenching in upper layers, and by photochemistry in outer layers (see Fig. 5.1). Other phenomena can also occur in different conditions.

5.2.1 Chemical Equilibrium

Under the chemical equilibrium assumption, the chemical composition depends only on temperature, pressure, and elemental abundances.

When the atmosphere of a planet is sufficiently hot and dense to ensure that chemical reactions occur faster than any other process, chemical equilibrium can accurately describe its composition. This can be the case of hot exoplanets with atmospheric temperatures in excess of $\sim 2000K$, while in the case of cooler planets it can be a good starting point to have an idea of which could be the main atmospheric constituents.

The atmospheric temperatures of gas giant planets may span over a broad range, from a few hundreds up to some thousands. Atmospheric composition is expected to be dominated by hydrogen and helium, with heavier elements present at a lower lever. Figure 5.2 shows various curves, calculated under chemical equilibrium for a solar elemental composition. The dashed lines in the plot delimitate the regions where either CH_4 or CO (red curve) or NH_3 or N_2 are the major reservoirs of carbon and nitrogen, respectively.

5.2.2 Disequilibrium Chemistry

When chemical reactions become slower than dynamic processes, the bulk composition can be driven out of chemical equilibrium. This happens, for example, in the cooler upper regions of the atmosphere. The consequence of the transport of material between different regions is a homogenization of heat and chemical composition, with a net flow from hot to cooler regions.

The vertical distribution of the atmospheric constituents can be strongly affected by the chemical quenching, a process in which as material moves upwards chemical reactions become slower, and at a certain level the abundances of the different

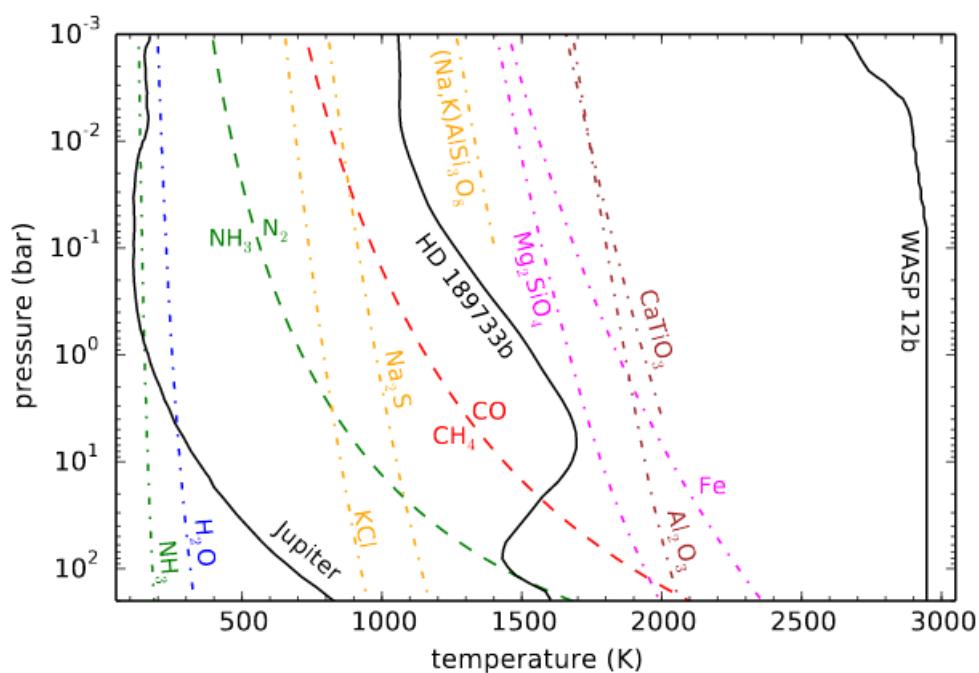


Fig. 5.2.: Pressure-temperature profiles for three gas giant planets covering a broad range of atmospheric temperatures: Jupiter (Lindal, 1992), the widely studied hot Jupiter HD 189733b (Agúndez et al., 2014) and the highly irradiated gas giant WASP-12b (Stevenson et al., 2014). Dot-dashed lines indicate the condensation curves for water, ammonia, and various refractory species containing Ca, Ti, Al, Fe, Mg, Na, and K. Image from Madhusudhan et al. (2016b).

species are progressively quenched. In gas giants exoplanets, chemical quenching regulates to a large extent the composition of the layers probed by observations. Horizontal distribution can also be influenced by chemical quenching when winds move material from hot to cooler atmospheric regions. In the usually tidally locked hot Jupiters, the uneven heating of the planet may result in important temperature contrasts, and thus in possible variations in the composition, between the day and night sides. The main effect of horizontal chemical quenching is that molecular abundances are quenched horizontally to values typical of the hottest day side regions, making the cooler night side to be contaminated by the warmer regions (Cooper and Showman, 2006; Agúndez et al., 2014). This effect is however more important as the atmospheres gets cooler and more marked for molecules such as H_2O , CO , and N_2 , which show rather uniform abundances, than for others such as CH_4 , NH_3 , and HCN , which may still show important abundance gradients among the different planetary sides (see Fig. 5.3).

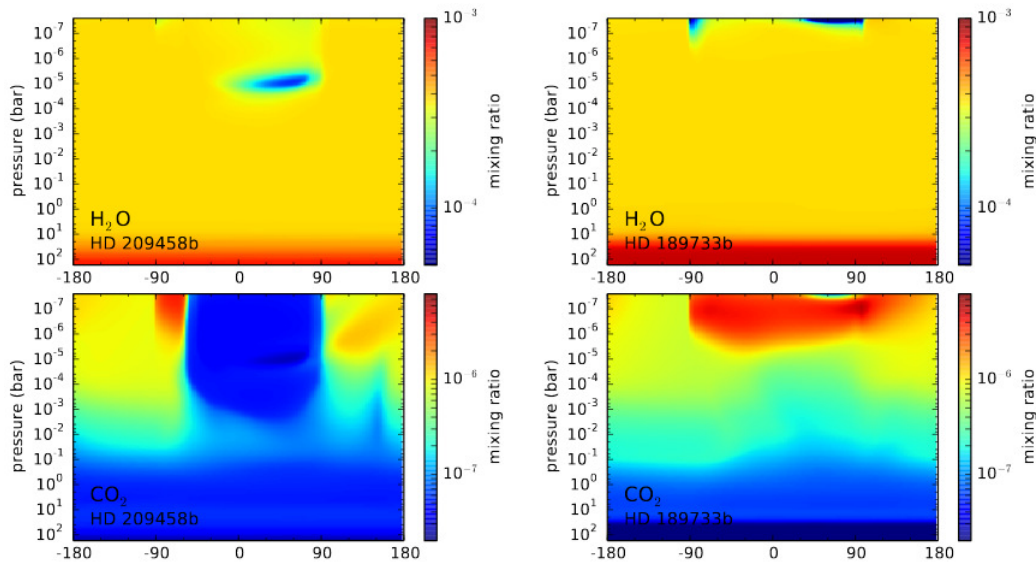


Fig. 5.3.: Calculated distributions of H_2O and CO_2 as a function of longitude and pressure in the atmosphere of HD 209458b and HD 189733b, from (Agúndez et al., 2014). Note that H_2O maintains a rather homogeneous distribution, while CO_2 experiences important abundance variations with longitude and height.

5.2.3 Photochemistry

Hot Jupiters are strongly irradiated by their host stars and thus receive a high ultraviolet flux. The upper atmosphere absorbs the incoming photons and parent molecules transported from deep atmospheric regions undergo photodissociation in

upper layers, producing radicals that react to form new species. The type of molecules formed by photochemistry depends on the composition of the precursor material transported from deeper layers, which in turn depends on the elemental composition and thermal atmospheric structure. On the one hand, higher temperature chemistry counterbalances the action of photochemistry, and on the other low temperatures favour the presence of CH_4 and NH_3 , which are more active photochemical precursors CO and N_2 .

There are various species produced by photochemistry in the atmospheres of gas giant planets. Since these atmospheres are hydrogen-rich, a major species produced by photochemistry is atomic hydrogen. Another important photochemical species is HCN , which formation is triggered by the photodissociation of CH_4 and NH_3 . The photodissociation of CH_4 also triggers the formation of larger hydrocarbons such as C_2H_2 and C_2H_6 , while the radical OH , produced by photodissociation of water, acts as a key intermediate in the synthesis of molecules such as O_2 and NO . In planets hot enough for refractory elements not being tied up in condensates, atomic neutrals and ions such as Mg , Mg^+ , Fe , Fe^+ , Ca , Ca^+ , Na , Na^+ , K , K^+ , Si^+ , Al^+ could be important photochemical and equilibrium species, although some dominant equilibrium molecular forms can also survive in the atmosphere.

5.2.4 Bulk Elemental Composition

Gas giant planets are expected to have nearly solar elemental compositions. However some may show a different metallicity and these deviations from the solar elemental composition can have a significant impact on the atmospheric composition.

In general, an enhancement of metallicity in H/He -dominated atmospheres of gas giant planets favors an increase in the abundances of molecules that contain multiple heavy atoms, that is CO and N_2 are favored over CH_4 and NH_3 . Molecules with more than two heavy atoms are even more favored (e.g., Zahnle et al., 2009a; Zahnle et al., 2009b).

In warm H/He -dominated atmospheres, one of the most critical elemental ratios is C/O . Under these conditions CO is highly stable and this makes it lock almost all the limiting reactant, either C or O . Then the reactants form O -bearing molecules such as H_2O when $\text{C}/\text{O} < 1$ and C -bearing molecules such as HCN and C_2H_2 when $\text{C}/\text{O} > 1$.

The observational claim of a carbon-rich atmosphere in the hot Jupiter WASP-12b (Madhusudhan et al., 2011) has opened a window on the possible existence of carbon-rich atmospheres and so to the existence of planets with a chemical dramatically different from the more traditional gas giants with a nearly solar C/O ratio (i.e.

oxygen-rich). In moderately warm and hot carbon-rich atmospheres, water is no longer the major constituent, and C-bearing molecules become major constituents. If the atmosphere is cool enough (< 1000 K) then CH_4 and H_2O become the main reservoirs of carbon and oxygen, respectively, at the expense of other carbon- and oxygen-bearing molecules (e.g., Moses et al., 2013a; Moses et al., 2013b; Venot et al., 2015).

5.2.5 Clouds and Hazes

The term cloud refers to the “cooling clouds” that form when a volume of gas is cooled dynamically or radiatively, such that the partial pressure of a constituent or constituents exceeds its saturation vapor pressure and condensation occurs. “Hazes” is restricted to aerosols that form in situ by the action of photochemistry or any other disequilibrium process or from photochemically produced gases flowing dynamically into cooler regions, where they can condense.

In Jupiter, the atmosphere is so cold that water and ammonia condense to form tropospheric clouds. In most extrasolar giant planets, the temperature is so high that water vapor and other volatiles survive in their atmospheres. In hot Jupiters, only the most refractory species can condense to form clouds. At temperatures of about 2000 K, aluminum, titanium, and calcium are expected to be the first elements to be removed from the gas phase, condensing as corundum, Ca-aluminates, and Ca-titanates.

At temperatures below ~ 1800 K, iron is expected to condense, and magnesium, together with a good fraction of silicon, are expected to deplete in the form of silicates such as Mg_2SiO_4 and MgSiO_3 . The presence of such type of clouds has been inferred from transit observation of the hot Jupiter HD 189733b (e.g., Pont et al., 2008; Etangs et al., 2008; P. Gibson et al., 2012). The alkali metals Na and K can be depleted in the form of aluminosilicates at temperatures around 1500 K, but in sufficiently hot atmospheres neutral Na and K atoms can survive in the gas phase and can be detected through the Na I doublet at 589.0 nm and 589.6 nm and the K I doublet at 766.5 nm and 769.9 nm (e.g., Charbonneau et al., 2002; Sing et al., 2011; Murgas et al., 2014; Wyttenbach et al., 2015).

Theoretical studies about the photochemical formation of organic hazes in the atmospheres of hot Jupiters expect that

- In hotter atmospheres most carbon remains locked into CO;

- In cooler atmospheres, the amount of carbon stored in CH_4 can be photochemically driven to larger hydrocarbons, eventually producing hydrocarbon aerosols.

This scenario agrees with observations in the Solar System (e.g., Zhang et al., 2013), although it is in contradiction with the inference of aerosols in the very hot atmosphere of WASP-12b (Sing et al., 2013).

More work is needed in both theoretical and observational sides to better understand the formation and role of clouds and hazes in extrasolar giant planets.

5.3 Exo-Neptunes and Super-Earths Atmospheric Chemistry

Thermochemical equilibrium, disequilibrium quenching, and disequilibrium photochemistry, the same processes discussed for giant planets, also affect smaller planets, but the basic ingredients available to the atmospheres of these planets differ from those of gas giants.

The parameters that control how massive the planet becomes, what atmospheric volatiles are collected, and how much atmospheric hydrogen and helium are retained emerge early in the planet's evolution, arising already from the dust/planetesimal surface density distribution and the planet's initial formation and feeding-zone location within the protoplanetary disk, and the planet's migration history (e.g., D'Angelo et al., 2010; Dodson-Robinson and Bodenheimer, 2010; Helling et al., 2014).

According to theory, protoplanetary cores form from the accretion of solid planetesimals, and gas accretion rates are initially slow. As the solid core grows, it can accrete more and more of the surrounding hydrogen-rich nebular gas (e.g., Lammer et al., 2014; Stökl et al., 2015). Eventually the protoplanet reaches a gas-accretion phase in which the nebular gas is rapidly accreted onto the protoplanetary core and this type of planets become hydrogen- or helium-rich gas giant planets. If this gas-accretion phase is not reached, intermediate-sized planets will form.

This chapter will not focus on these planets, the so-called super-Earths, mini-Neptunes and Neptune-sized planets, with radii spanning $\sim 1 - 6R_{\oplus}$, as because the atmospheric characterization of these objects was beyond the purpose my PhD studies. Observations show that these objects constitute a large percentage of the known planets in our galaxy (e.g., Borucki et al., 2011; Rowe et al., 2015), and

typically have higher atmospheric metallicity (thus they contain less hydrogen and helium) than giant planets because of the less efficient accretion of nebular gas during their formation and evolution, as well as the higher likelihood of the escape of light gases over time. Outgassing from the planetary interior is a process that probably contributes additional volatiles. Other evolutionary processes such as atmospheric escape, impact delivery or erosion, atmosphere-surface exchange, weathering, and sequestration of volatiles into the interior are expected to have a major influence on atmospheric composition and chemistry. Exo-Neptunes, super-Earths, and smaller, hot, rocky planets follow different evolutionary pathways and this is expected to lead to highly diverse atmospheric properties.

5.4 Habitable Exoplanets: What Do We Currently Know?

The search for life beyond Earth is one of the most monumental endeavors on which humanity has ever embarked. Our definition of life is necessarily limited by our understanding of life on Earth and was described as an open system that requires three essential components:

1. An energy source to drive metabolic reactions;
2. A liquid solvent to mediate the reactions;
3. A suite of nutrients both to build biomass and to produce enzymes that catalyze metabolic reactions.

The study of life on our planet and the general principles of chemistry and physics further suggest that liquid water has some important characteristics that make it the best solvent for life. It is one of the most abundant compounds in our galaxy, that is possible to find in different environments, and its distinct physicochemical properties make it highly suitable for mediating macromolecular interactions. Carbon chemistry is likewise favored as a basis for biomass because carbon is the only chemical element with the ability to form an inordinate number of complex molecules. However, these two assumptions are made provisionally. Alternative biochemistries may exist, their plausibility has not yet been convincingly demonstrated.

The most defining aspect of life is the capacity for evolution, which is necessary to adapt organisms to changing environmental conditions. This requirement to engage in evolutionary adaptation likely requires complex functional molecules that

preclude environments too extreme to allow the formation and long-term persistence of such molecules (e.g., Des Marais, 2013).

5.4.1 Biosignatures: Detecting the Presence of Life

A sign of life from an exoplanet may manifest itself as a spectroscopic signal, a measurement that will have a stated uncertainty and potentially a range of explanations. The presence of a gas or surface feature can be inferred then from that signal and may be interpreted as originating from a living process. This type of signal is called biosignature and it is defined as an “object, substance and/or pattern whose origin specifically requires a biological agent” (Des Marais and Walter, 1999). In practice, we consider an exoplanet biosignature a potential biosignature with other possible explanations. This statement protects against false positives, all the unknown fake signals given by full range of abiotic chemistries that might mime the true signature of life.

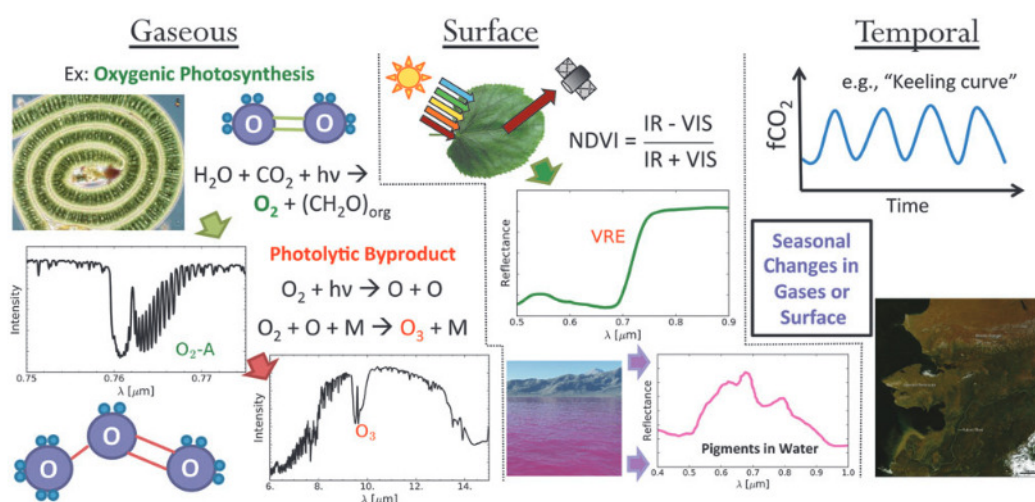


Fig. 5.4.: *Left panel:* gaseous biosignatures are direct or indirect products of biological processes. One example is molecular O_2 generated as a by-product of photosynthesis that is then photochemically processed into O_3 in the stratosphere. *Middle panel:* surface biosignatures are the spectral signatures imparted by reflected light that interacts directly with living material. One example is the well-known vegetation red edge (VRE) produced by plants and the associated Normalized Difference Vegetation Index (NDVI) used for mapping surface vegetation on Earth (Tucker, 1979). *Right panel:* time-dependent changes in observable quantities, including gas concentrations or surface albedo features, may represent a temporal biosignature if they can be linked to the response of a biosphere to a seasonal or diurnal change. An example is the seasonal oscillation of CO_2 as a response to the seasonal growth and decay of vegetation. Image from Schwieterman et al. (2018).

There is currently no universally accepted scheme for classifying the potential exoplanet signatures. For convenience, biosignatures are grouped into three broad categories (Meadows, 2008): gaseous, surface, and temporal biosignatures (Fig. 5.4). In this scheme, gaseous biosignatures are direct or indirect products of metabolism, surface biosignatures are spectral features imparted on radiation reflected or scattered by organisms, and temporal biosignatures are modulations in measurable quantities that can be linked to the actions and time-dependent patterns of a biosphere.

5.4.2 Conditions for Planetary Habitability

Habitability is a condition that derives from the complex interplay among instellation, atmospheric dynamics, greenhouse gases, planetary tectonics, orbital stability, ice-albedo feedbacks, the remote detectability of these processes, and many other parameters. The evaluation of biosignatures must include some discussion of habitability. Inhabited planets are habitable and detectable metrics for habitability will assist in the interpretation of potential biosignatures. One of the critically necessary conditions for a planet to harbor life is permanent existence of liquid water on the planet's surface. To maintain liquid water, the planetary surface temperature has to be between the freezing point of water and the boiling point, that is, at 1 bar,

$$0^{\circ}\text{C} < T_s < 100^{\circ}\text{C}. \quad (5.2)$$

In reality, the boiling point of water is not the true limit, but the upper limit of surface temperature has to be lower or the planet would fall into the runaway greenhouse state. Moreover, the planetary mass has to be sufficiently large, so that the planet has a surface gravity large enough to retain a fairly dense atmosphere and a large amount of water against escape processes.

However, the planetary mass cannot be too large or the planet could have accreted a massive H_2/He envelope whose greenhouse effect along with the high pressure of the envelope would warm the surface and prevent water from being liquid, or it could be a Neptune-like ice-giant planet (Venturini et al., 2015). Specifically Selsis et al. (2007) stated that a habitable planet has to be a solid planet, with a mass in an approximate range given by:

$$0.5M_{\oplus} < M < 10M_{\oplus} \quad (5.3)$$

The first condition was used by Shapley (1953) to define a circumstellar zone, later called Habitable Zone (HZ) by Huang (1960), in which a terrestrial planet can hold permanent liquid water on its surface. This definition was expanded in later works

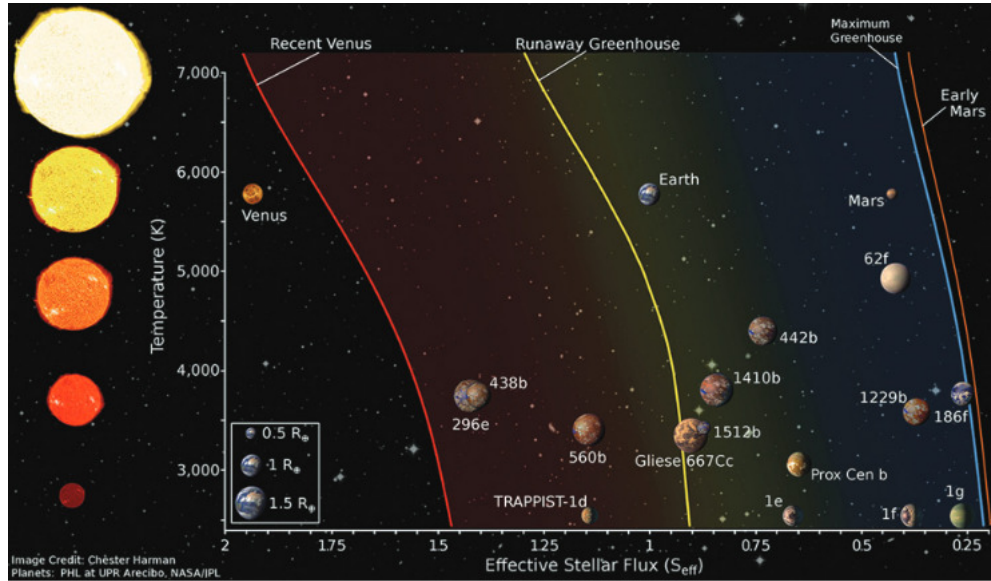


Fig. 5.5.: The circumstellar habitable zone. Planets within the Habitable Zone have the capacity to maintain stable surface liquid water assuming an N_2 - CO_2 - H_2O atmosphere and a carbonatesilicate feedback cycle (Kopparapu, 2013). The assumption of surface liquid water is important because it suggests a biosphere, if present, would be in direct contact with the atmosphere, allowing the buildup of potentially detectable biosignatures in the atmosphere and/or on the surface.

(e.g., Kopparapu, 2013), based on results from one-dimensional radiative-convective climate models. According to these works, several parameters, such as surface albedo, atmospheric compositions, and stellar radiation spectra, need to be taken into account to calculate the width of the HZ (see Fig. 5.5). The boundaries of the HZ in terms of instellation vary as a function of stellar type as the spectral energy distribution of stars of different temperatures produces different effective planetary albedos even for a planetary atmosphere of constant composition. Kasting et al. (1993) addressed how the inner and outer edges of HZ are constrained by the positive water-vapor feedback and by the saturation limit of the maximum CO_2 concentration, respectively.

However, the inner edge of HZ is not at the distance where planetary surface temperature is equal the boiling point of water ($100^\circ C$), as one might expect. In fact, as shown by Ingersoll (1969), all liquid water on the planetary surface would completely evaporate into the atmosphere due to the positive water-vapor feedback once the surface temperature reaches about $70^\circ C$, and the planet falls into the runaway greenhouse climate state. Then, water would be lost throughout photolysis

and hydrogen escape. The outer edge is constrained by the limit of CO₂ saturation, with which CO₂ condensation begins to take place. Thus, further increasing CO₂ does not enhance the greenhouse effect.

Other definitions of the HZ are much broader and the newest works include advanced three-dimensional general circulation models. Confirming habitability requires further investigation beyond simply determining whether a planet lies within the HZ of its star. The most straightforward determination of planetary habitability would be direct detection of surface liquid water, possibly through the observation of glint if the planet can be observed at large phase angles (Robinson et al., 2014), while time-dependent spectrophotometric analysis could detect ocean-land heterogeneity and rotation rate (e.g., Cowan and Strait, 2013) and may also provide indirect evidence for other consequences of continentality, including terrestrial habitats, plate tectonics, and attendant nutrient cycling.

Using Spectroscopy for Characterizing Exoplanetary Atmospheres

Mass and radius measurements alone cannot uniquely constrain the bulk composition of the planets we observe, because of the degeneracies between models, and the relative uncertainties of the measurements (e.g., Adams et al., 2008). The only means for distinguishing the composition of a planet's outer envelope is provided by atmospheric characterization.

As we have seen in Chapter 5, planetary atmospheres are primarily composed of molecules or, as in the case of hot planets, neutral and ionized atoms. The relative abundances of different molecular species depend on the complex interplay between many factors: atmospheric dynamics and circulation, photo-chemistry, disequilibrium processes and initial bulk composition.

The spectral properties of the light that originates from the planet are determined by the thermal, chemical and material properties of its outer layers. So, to learn more about a planet, it is necessary to study the light from the star that passes through its atmosphere: spectroscopy is the best way to do it.

Stars generally emit most of their radiation at optical wavelengths. A fraction of this light is absorbed and heats the atmosphere, and the planet reflects the rest back into space. The spectrum of an exoplanet is then the result of two distinct components: the star light, reflected or scattered by the planet, and the light that is emitted by the planet itself.

The fraction of starlight reflected by the planet is the Bond Albedo, a quantity that, combined with any heat sources in the interior of the planet, determines the energy budget, allowing the determination of the overall temperature. To first order, the planet re-emits the absorbed starlight like a black-body, so the temperature of the planet can be constrained by measuring the amount of thermal radiation, possibly in multiple bands (e.g., Charbonneau et al., 2005; Knutson et al., 2007; Demory et al., 2016).

The geometry of the transit offers the possibility of transmission spectroscopy: when the starlight passes through the optically thin outer layers of the atmosphere the traces of the absorption from the chemical constituents of the atmosphere are imprinted in the spectrum (e.g., Brown, 2001; Charbonneau et al., 2002; Snellen et al., 2008; Sing et al., 2011).

In the following sections of this Chapter, specific detections of exoplanet atmospheres and the observational techniques used to complete these studies will be discussed.

6.1 The Emission and Reflection Spectrum

The orientation of the system makes the isolation of the planet's emission or reflection spectrum possible. Only the planet's hemisphere facing its host star will reflect light. Due to the planet orbital motion and our fixed vantage point, we are not always able to see the whole illuminated hemisphere, but a fraction of it, limiting the reflected flux we receive from the planet. As seen from Earth, the planet will exhibit phases of changing brightness, similar in appearance and behaviour to the changing phases of the Moon. Due to orientation, the planet's night-side will be fully visible during transit and its day-side will be almost fully visible just before and after the secondary eclipse.

Whether a planet's phase curve is measuring surface brightness due to emitted light or reflected light, depends on the wavelength of the observations and the temperature of the star and planet. A phase curve can be created by a combination of emitted and reflected light, where the contribution for reflected light is commonly assumed to be visible in the optical part of the spectrum, at wavelengths dominated by the star's blackbody, and emitted light contribution is visible in the infrared part of the spectrum, at wavelengths where the planet's blackbody is stronger.

The amount of reflected light can be quantified in terms of a Lambertian surface a flat, perfectly diffusing disk with the same cross-sectional area as the planet. The total reflected light signal is

$$F_{\text{ref}} = A_g \cdot \frac{R_p}{a} \cdot \Phi(\alpha) \quad (6.1)$$

where α is the orbital separation and $\Phi(\alpha)$ is the phase function (the reflected light intensity at phase angle α), and A_g is the geometric albedo, which is defined as the ratio of a planet's flux measured at opposition ($\alpha = 0$) by the flux of a Lambertian disk at the same distance and with the same radius as the planet.

The dominant source of thermal emission of a planet is re-radiation of incident stellar flux, especially for the short-period planets that have been studied so far. Thus the typical size of the emission signal can be predicted from the planet's equilibrium temperature, and the observed planet-star flux ratio is then:

$$\frac{F_p}{F_\star} \approx \frac{B(\lambda, T_{\text{eq}})}{B(\lambda, T_\star)} \cdot \left(\frac{R_p}{R_\star}\right)^2 \quad (6.2)$$

where $B(\lambda, T)$ is the Planck function corresponding to the brightness temperature T , $T_\star$ is the effective temperature of the star and T_{eq} is the planetary equilibrium temperature

$$T_{\text{eq}} = T_\star \cdot \left(\frac{R_\star}{a}\right)^2 (f \cdot (1 - A))^{1/4}. \quad (6.3)$$

In Eq. 6.3, a is the semi-major axis, A is the bond albedo and f is the heat redistribution factor of the planet's atmosphere.

Since the planet is cooler than the star, the flux ratio is larger at longer wavelengths. However, it is important to note that Eq. 6.2 is just a first order approximation of the planet signal, since more complex features arise in the spectrum due to the atmosphere's changing opacity with wavelength.

Figure 6.1 shows a diagram of a planet at various phases and the associated overall brightness of the star-planet system.

6.2 Transmission Spectrum

The transmission, or absorption, spectrum of an exoplanet's atmosphere can be measured during transit using multi-wavelength observations. These measurements are possible because, when the planet passes in front of its star, a fraction of the stellar disc will be covered by the gaseous envelope that surrounds the planet. As the starlight passes through the upper atmospheres, characteristic spectral signatures are superimposed on the light as it is absorbed or scattered.

The planet's absorption spectrum is directly related to the opacity of the planet at different wavelengths, then, by modeling the amount of light absorbed at different wavelengths, a number of different atmospheric properties and constituents can be determined. This effect manifests itself as a wavelength-dependence of the effective radius of the planet. At the wavelength of an atmospheric absorption line, the atmosphere is less transparent than at other wavelengths, so inside the line, the planet causes a slightly deeper transit and will hence appear to be larger. Assuming that the opacity of the atmosphere decreases with altitude, this implies that the

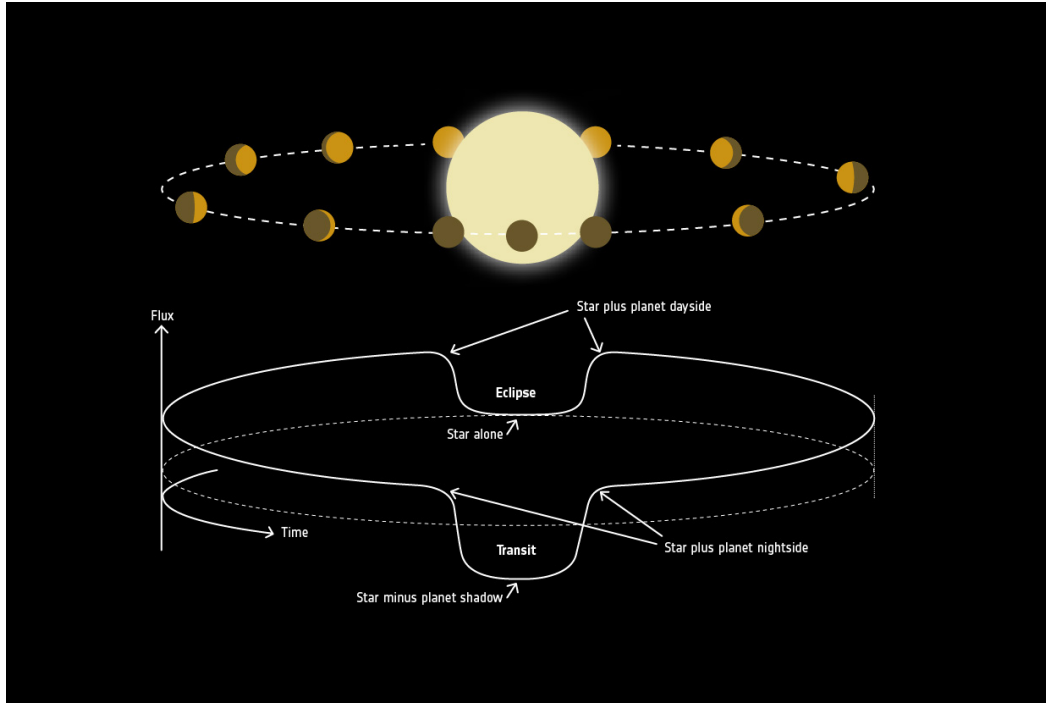


Fig. 6.1.: *Top diagram:* depiction of the surface brightness of a planet at different phases in its orbit. *Bottom diagram:* plot of the total brightness of the star-planet system at associated phases. Credits: <https://www.esa.int/>

core of the line is formed high up in the atmosphere, whereas the wings of the line originate from deeper layers of the atmosphere. At the same time, the width of a spectral line depends on the local temperature and pressure. Therefore, the shape of an absorption line can in principle be used to constrain the thermal structure of the atmosphere (e.g., Sing et al., 2008; Vidal-Madjar et al., 2011).

To order of magnitude, the depth of spectral features in transmission is then

$$\delta_{\lambda} = \frac{(R_p + nH)^2}{R_{\star}^2} - \frac{R_p^2}{R_{\star}^2} \approx 2n \cdot \frac{R_p \cdot H}{R_{\star}^2} \quad (6.4)$$

where H is the scale height as defined in Eq. 5.1 of Chapter 5 and n is the number of scale heights crossed at wavelengths with high opacity.

It immediately follows that ideal candidates for transmission spectroscopy have high equilibrium temperatures, small host stars, low surface gravity, and low mean molecular mass composition. However, it is worth noting that even for these ideal cases, the amplitude of spectral features is just $\delta_{\lambda} \sim 0.1\%$ and that, for Earth-like planets, the expected amplitude is two to three orders of magnitude smaller, depending on host star size.

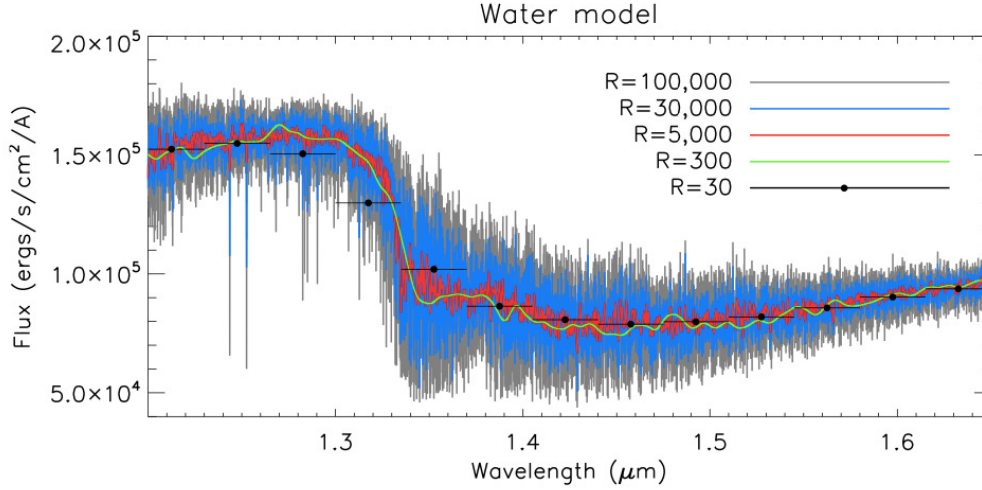


Fig. 6.2: The effect of decreasing spectral resolution. The panel shows a wavelength region of a model hot Jupiter atmosphere containing water, convolved to different spectral resolutions. Image from Birkby et al. (2013a).

6.3 Spectral Resolving Power

Spectroscopy, as it pertains to exoplanet observations, is the measurement of a light curve at multiple wavelengths using either a spectrograph or multi-detector array. As a result, exoplanet transmission spectroscopy is limited to planets around bright, and therefore nearby, stars and can best detect absorption features from large and diffuse atmospheres, like those on Jovian-type planets. Emission spectroscopy is also limited to nearby planetary systems and are best detected in large planets with hot atmospheres, such as Jovian planets that orbit very close to their parent star. The resolving power $\mathcal{R}$ of a spectrograph describes the spectral scale that can be resolved in a spectrum at wavelength λ :

$$\mathcal{R} = \frac{\lambda}{\Delta\lambda} \quad (6.5)$$

Based on the subject of study, it is possible to adopt two different approaches to study exoplanetary atmospheres: broad- and narrow-band transmission spectroscopy, using low- and high-resolution instruments respectively. Both techniques are complementary, as they allow us to retrieve diverse characteristics of the planetary atmosphere.

The community is moving towards the combined analysis of the two techniques (e.g., Brogi et al., 2017; Pino et al., 2018), a crucial effort for characterizing in depth

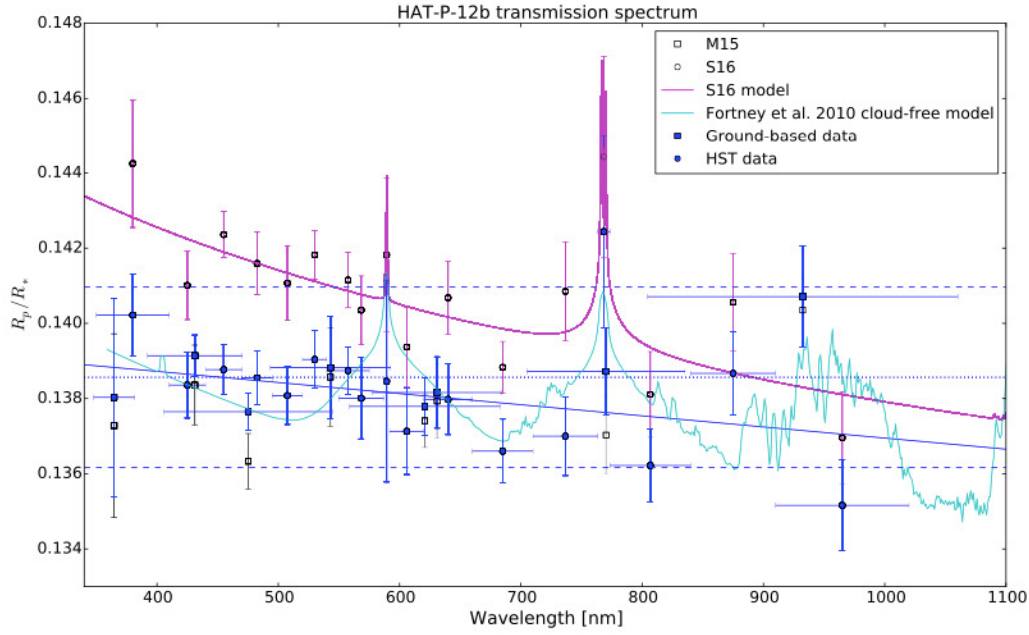


Fig. 6.3.: Transmission spectrum of HAT-P-12 b as derived from the homogeneous reanalysis of all data from the ground and from the HST with their associated error bars. The blue squares show the data taken from ground with TNG/DOLoRes (Alexoudi et al., 2018). This study helped solving the controversial results obtained by Mallonn et al. (2015) and Sing et al. (2016).

exoplanets and understanding their formation history and evolution. The combined analysis will allow us to define the T - P profile and continuum level of the planet, thus removing degeneracies with composition.

6.3.1 Low to Medium Resolution Spectroscopy

Low- to medium- resolution ($\mathcal{R} \sim 100 - 1,000$) spectrographs are used to obtain the broad-band transmission spectra, at wavelengths ranging from the ultra-violet ($\sim 0.3 \mu m$) to the mid-infrared ($\sim 24 \mu m$), allowing us to infer whether clouds or hazes are present in the atmosphere of the observed planet (Fig. 6.2). The presence of hazes can be inferred from the shape of the scattering slope in the blue part of the optical spectrum, while the presence of clouds is one possible explanation for observing a featureless spectrum towards the red wavelengths. During the transit observation, spectra from the host star as well as at least one reference star in the field are captured to apply spectrophotometry in wavelength bins of 50-100 Å.

In the optical to the near-infrared, several telescopes, based both on the ground and in space, have been used to observe planetary spectra. From space, optical

observations with the Hubble Space Telescope (HST) instruments ACS (Advanced Camera for Surveys) and STIS (Space Telescope Imaging Spectrograph) led to the detection of an enhanced optical slope in the transmission spectra of several exoplanets (e.g., Etangs et al., 2008; Pont et al., 2008; Sing et al., 2016) and of the strongest spectral features, such as the sodium and potassium doublets (e.g., Charbonneau et al., 2002; Sing et al., 2015). At near-infrared wavelengths, HST's Near Infrared Camera and Multi-Object Spectrometer (NICMOS) and Wide Field Camera 3 (WFC3) observations allowed us to firmly detect many species and spectral features in exoplanet atmospheres, such as water and aerosols (e.g., Crouzet et al., 2012; Knutson et al., 2014; Kreidberg et al., 2015).

From the ground, Earth's atmosphere is a huge hindrance because it has many of the spectral features we might look for in the spectrum of an exoplanet. Moreover, it is also turbulent, meaning that the exact shape of its spectral features may change with the weather. Differential spectro-photometry using low resolution spectrographs allows to avoid confusing changes in the Earth's atmosphere with changes in the atmosphere of an exoplanet, simultaneously observing a comparison star and the transit. This technique deletes any atmospheric effects dividing the comparison star's spectrum by the host star's spectrum, reducing the noise to Poisson noise only. Despite the limitations of ground-based spectroscopy, instruments like DOLoRes mounted at TNG proved their effectiveness (Fig. 6.3), obtaining interesting results comparable with the ones obtained with space instrumentation (e.g., Alexoudi et al., 2018).

6.3.2 High Resolution Spectroscopy

The configuration required to convert a small dispersion angle to a large dispersion distance on the detector currently makes high resolution spectrographs available only for ground-based telescopes. The spectral resolution increases dramatically ($\mathcal{R} \geq 30,000$), increasing the contrast of absorption features in exoplanetary spectra.

High resolution spectroscopy (HRS) is rooted in the Doppler method and uses the difference in radial velocity, between the star and the planet, to isolate the planetary absorption, or emission, spectrum (Fig. 6.4). The Doppler method allows us to gather the star's radial velocity along our line-of-sight, given by Eq. 1.6, but, unlike other spectroscopic methods, Doppler spectroscopy does not produce a planet spectrum.

Instead, the planet spectrum superimposed on to the star's absorption spectrum. Since the star, compared to the planet, confers a significantly larger orbital velocity

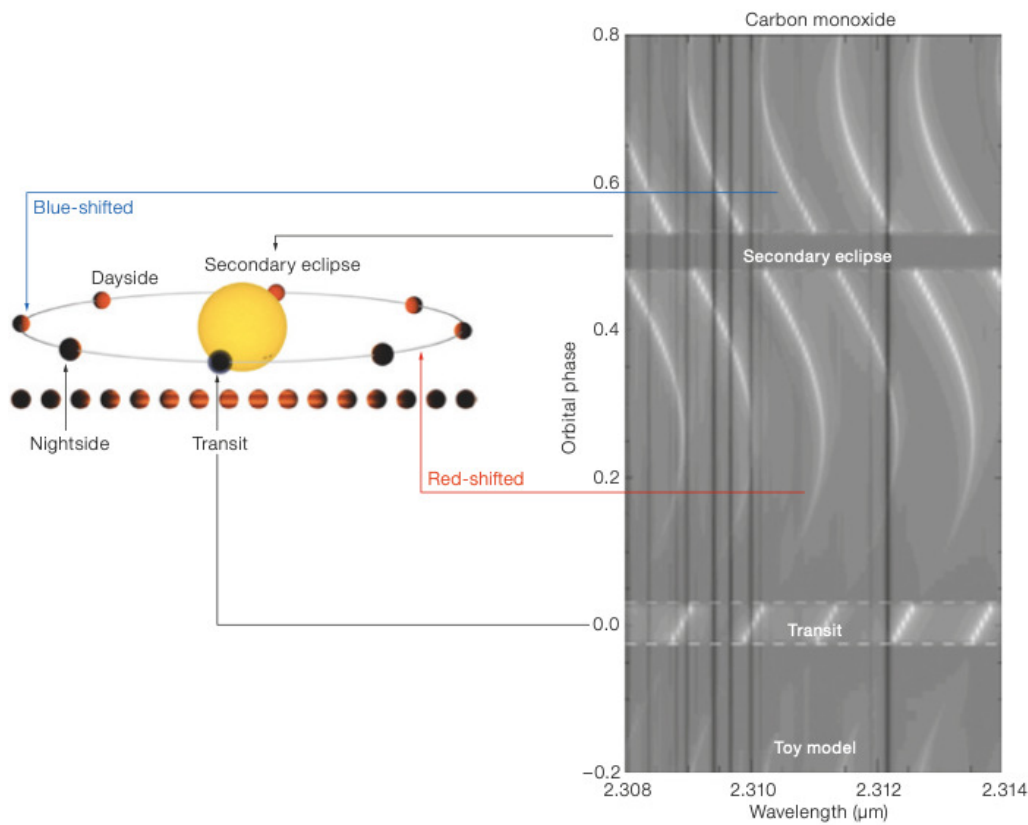


Fig. 6.4.: Schematic of high-dispersion spectroscopic observations for detecting molecules (carbon monoxide in the example) in the thermal spectrum of a hot Jupiter. The white curved lines trace out the radial velocity of individually resolved lines in the carbon monoxide molecular band, which, throughout the orbit, significantly shift in wavelength owing to the change in the radial component of the exoplanet orbital velocity. The dark vertical features are telluric absorption, which is stationary with time, allowing the disentanglement destroying the planetary signal. Image from Birkby et al. (2013a).

to the planet, this has a radial velocity that is typically orders of magnitude faster than the star. Consequently, the red- and blue-shift of the planetary spectral features are much larger than the stellar ones, that result essentially stationary by comparison. If the planet's orbital parameters are known, the velocity change can be predicted and variations at the star's velocity can be removed without completely erasing the planet's signal.

For ground-based observations, absorption lines from the Earth's atmosphere, also known as telluric lines, represent a contamination that must be taken into account. Using the same procedure as for the stellar lines, telluric lines can be mitigated, but result in less detection strength, especially when searching for elements or molecules that are also in Earth's atmosphere, such as water. The procedures used to mitigate telluric lines are described later in this Chapter.

This method has been used to measure the absorption due to individual atomic lines, such as those of the sodium and magnesium (e.g., Wyttenbach et al., 2015; Wyttenbach et al., 2017) but also heavier elements in the most extreme cases (e.g., the iron lines in KELT-20 b as found by Casasayas-Barris et al., 2019), where excess absorption, or emission, is observed at the planet's velocity. The comparison of the observational measurements with the exoplanetary atmospheric models allows to constrain the characteristics of the atmosphere such as the number densities of the species and the temperature-altitude profile.

Although we can use the Doppler shift to find absorption due to elements and molecules, the planet spectrum is buried in the noise of the stellar spectrum and the increased spectral resolution aspect becomes crucial to overcome the significant challenge of the planet-to-star flux contrast ratio, which ranges from 10^3 to 10^{10} for hot Jupiters to Earth-Sun analogues, respectively. Each spectral line of the planet spectrum is detectable to a certain significance, and the deeper the line, the easier it is to detect. Including more lines in our measurement, increases the significance of our detection, because by detecting multiple spectral lines, we boost the signal-to-noise of the planet by the square root of the number of lines we detect. For a close-in exoplanet, following Snellen et al. (2015) and assuming that we can completely remove the contaminating effects of the Earth's atmosphere, the signal-to-noise ratio of the planet spectrum obtained via HRS is

$$SNR_p = \frac{S_p \cdot \sqrt{N_{\text{lines}}}}{\sqrt{S_\star + \sigma_{\text{bg}}^2 + \sigma_{\text{read}}^2 + \sigma_{\text{dark}}^2}} \quad (6.6)$$

where S_p and $S_\star$ are the signal from the planet and star respectively, both in units of photons per resolution element, σ_{bg} is the noise from the sky and telescope

background, σ_{dark} the read-out noise, σ_{dark} the dark current from the detector and N_{lines} represents the number of lines detected in the observed wavelength range.

After telluric and stellar lines are removed from the spectra, we are left with the residuals which contain noise and the planet's spectral lines. The individual planet lines have low signal-to-noise and it is necessary to combine their signals to detect the planet spectrum. The cross-correlation method is one of the most powerful approaches to do this. This technique effectively measures the degree of similarity between the residuals of each observation and a template spectrum appropriate for the planet atmosphere and compares how well the template matches the specific line positions and the ratio of the line depths in the observed planet spectrum. This method has been widely used to find molecules such as CO and H₂O in the infrared (e.g., Snellen et al., 2010; Brogi et al., 2012; Brogi et al., 2013; Birkby et al., 2013b), but also for the detection of trace metallic elements in the atmosphere of ultra-hot Jupiters (e.g., Hoeijmakers et al., 2019) in the visible wavelengths.

6.4 Hot Jupiters

Prior to the discovery of the first exoplanets, our conception of planetary systems was informed by a single observational sample, our own Solar System. The discovery of the first gas giants outside of the Solar System, 51 Peg b, sparked a revolution in our view of planets and their formation and also ignited the fast progress of the field of exoplanetary science by inspiring extensive theoretical work on several physical processes that were missing from our pre-exoplanet knowledge.

The observed properties of hot Jupiters and their host stars are fundamental to test theories of their origins. Due to the combination of these properties, hot Jupiters provide a unique window into the nature of the exoplanet population, especially amenable for transmission spectroscopy during transit events.

Many observed hot Jupiters show radii larger than that expected even when taking surface heating from the star into account (e.g., Baraffe et al., 2010). The suggested inflation mechanisms are classified into three categories (Weiss et al., 2013): incident stellar flux-driven mechanisms, tidal mechanisms and delayed contraction. One intriguing explanation for incident stellar flux-driven mechanisms is the interaction between atmospheric winds and the planet's magnetosphere creating an electric current through the planet that heats it up, causing its expansion (e.g., Batygin et al., 2011). The hotter the planet, the greater the atmospheric ionization, and thus the greater the magnitude of the interaction and the larger the electric current, leading

to more heating and expansion of the planet. Tidal dissipation in a giant planet's interior produces heating that would stop or slow down the planet's contraction, but it was shown by Leconte et al. (2010) that this mechanism can explain moderately inflated planets, but cannot reproduce both the orbital parameters and radius of very inflated planets. Enhanced atmospheric metallicities or alteration of atmospheric properties may lead to enhanced opacities, reducing interior heat transport efficiency and slowing down these planets cooling and contraction (e.g., Chabrier and Baraffe, 2007).

Either we are still missing some important physics in planetary interiors, or that the solution does not reside in an unique mechanism but in a combination of the various processes, the improvement of the sample of hot Jupiters studied

The species present in a hot Jupiter's atmosphere are clues to where and how the hot Jupiter formed, since the composition of gas and grains in a protoplanetary disk varies radially as the disk temperature drops and volatiles condense.

The atmospheres of gas-giant planets are predominantly composed of molecular hydrogen and atomic helium, with the other molecules mainly dependent on the availability of carbon and oxygen, characterized by the C/O ratio. According to the hypotheses adopted in the models, the abundances of the different chemical species can be calculated as a function of pressure and temperature (as seen in Section 5.2). The expected molecules are, for example, H₂O (e.g, Birkby et al., 2017; Webb et al., 2020), CO (e.g, Brogi et al., 2013; Brogi et al., 2018), CH₄ and HCN (e.g., Guilluy et al., 2019), NH₃, PH₃, H₂S,. It is also possible to detect TiO and VO (e.g., Bourrier et al., 2020) in the hotter atmospheres. Other trace elements have been observed in the atmospheres of hot Jupiters. For example, alkali metals such as Na, K, and Li (e.g., Borsa et al., 2020; Seidel et al., 2020), have been found in many planets, and more recently the absorption lines of heavier elements have been detected in the hottest planets, the so-called ultra-hot Jupiters.

6.4.1 Ultra-hot Jupiters

Ultra-hot Jupiters belong to a new group of exoplanets, the hottest known until now, with equilibrium temperatures in excess of 2200 K (Parmentier et al., 2018). The reason for its high temperature is the proximity of its orbit around its host star, causing it to receive a large flux of radiation in the upper layers of its atmosphere. These planets are unique laboratories to study the impact of extreme stellar irradiation on the evolution of planetary atmospheres. Most molecules and aerosols cannot resist these environment high temperatures, hence models predict clear atmospheres mainly composed by atoms and ions. Several ultra-hot Jupiters have been studied

and have shown interesting characteristics. Focusing on transmission spectroscopy at high resolution, the study of the atmosphere of KELT-9 b, the hottest planet known to date ($T_{\text{eq}} = 4050$ K and day-side temperature of 4600 K), showed the presence an extended atmosphere of $\text{H}\alpha$ produced by irradiation (Yan and Henning, 2018), Hoeijmakers et al. (2018) detected FeI, FeII and TiII, and Cauley et al. (2019) further reported the detection of $\text{H}\beta$ and of the MgI triplet, concluding that at this high temperatures metals are preponderantly in their ionic forms. Also MASCARA-2 b/KELT-20 b (Lund et al., 2017a; Talens et al., 2018a) has been observed extensively with the HARPS-N and CARMENES spectrographs, leading to detections of two Balmer lines of hydrogen, the NaI D-lines, the CaII infrared triplet, FeI, FeII and MgI lines (Casasayas-Barris et al., 2018; Casasayas-Barris et al., 2019; Stangret et al., 2020a; Nugroho et al., 2020).

Characterizing the Atmosphere of Hot Jupiters

In this Chapter I will present my work in exoplanet atmospheres characterization. I will focus on the methods I have developed during my PhD Course for the analysis of exoplanetary atmospheres and I will present the results of two cases I have studied: KELT-9 b and KELT-20 b, two ultra-hot Jupiters orbiting around two hot stars.

7.1 Two Ultra-hot Jupiters: KELT-9 b and KELT-20 b

Transiting ultra-hot Jupiters (UHJs) are ideal laboratories to study planetary atmospheres: their inflated atmospheres and high equilibrium temperatures (T_{eq}) result in strong signals and striking peculiar conditions for a planetary body.

KELT-9b (Gaudi et al., 2017) is a ultra-hot Jupiter that orbits a fast rotating A-type star (A0, $T_{\text{eff}} = 9600$ K, $m_V = 7.56$). With a period of 1.48 days and a semi-major axis of 0.03368 au, KELT-9b is highly irradiated by its host star and its atmosphere reaches $T_{\text{eq}} = 4050$ K.

KELT-20b (Lund et al., 2017b), aka MASCARA-2b (Talens et al., 2018b), is a well known ultra-hot Jupiter orbiting a fast rotating A-type star (A2, $T_{\text{eff}} = 8980$ K, $m_V = 7.6$), highly irradiated, with a period of 3.47 days and a semi-major axis of 0.0542 au. KELT-20b's atmosphere reaches $T_{\text{eq}} = 2260$ K.

Table 7.1 reports more details for the two systems.

7.2 GAPS Consortium Atmospheres Project

The GAPS Consortium, has funded and built GIARPS, the GIANO + HARPS-N simultaneous observing mode of the TNG, precisely to exploit the full potential of the simultaneous VIS + NIR HRS technique, using primary transit observations of a large sample of low-density giant planets with a wide range of masses, radii, and irradiation conditions, orbiting around stars with a range of spectral types. The

Tab. 7.1.: Physical and orbital parameters of the KELT-9 and KELT-20 systems

Parameter	Symbol	KELT-9	KELT 20
Stellar Parameters			
Spectral type		A0	A2
V-band magnitude	m_V	7.56	7.6
Effective temperature	T_{eff} [K]	9600 ± 400	8980^{+90}_{-130} K
Projected rotation speed	$v \sin i_*$ [km s ⁻¹]	111.8 ± 1.1	116.23 ± 1.25
Surface gravity	$\log g$ [cgs]	4.1 ± 0.3	4.31 ± 0.02
Metallicity	[Fe/H] [dex]	0.14 ± 0.30	-0.02 ± 0.07
Stellar mass	M_* [$M_\odot$]	2.32 ± 0.16	$1.89^{+0.06}_{-0.05}$
Stellar radius	R_* [$R_\odot$]	2.418 ± 0.058	1.60 ± 0.06
Planetary parameters			
Planet mass	M_p [M_{Jup}]	2.88 ± 0.35	< 3.51
Planet radius	R_p [R_{Jup}]	1.936 ± 0.047	1.83 ± 0.07
Planet-to-star ratio	R_p/R_*	0.08228 ± 0.00043	$0.11440^{+0.00062}_{-0.00061}$
Equilibrium temperature	T_{eq} [K]	3921^{+182}_{-174}	2260 ± 50
Surface gravity	$\log g_p$ [cgs]	$3.279^{+0.053}_{-0.058}$	< 3.46
Orbital parameters			
Epoch	T_P [BJD]	$2\,457\,095.6857 \pm 0.0001$	$2\,457\,909.5906^{+0.0003}_{-0.0002}$
Period	P [days]	1.481123 ± 0.000001	$3.474119^{+0.000005}_{-0.000006}$
Transit duration	T_{dur} [days]	0.16316 ± 0.00016	$0.14882^{+0.00092}_{-0.00090}$
Semi-major axis	a [au]	0.03368 ± 0.00078	$0.0542^{+0.0014}_{-0.0021}$
Inclination	i [deg]	86.79 ± 0.25	$86.15^{+0.28}_{-0.27}$
Eccentricity	e	0 (fixed)	0 (fixed)
Radial velocity semi-amplitude	K_s [m s ⁻¹]	293 ± 32	< 322.51
Systemic velocity	V_{sys} [km s ⁻¹]	19.819 ± 0.024	-23.3 ± 0.3

goal of this extensive search is to identify the individual contributions from the different atoms and molecules, to constrain the impact of the poorly understood hazes and clouds that often appear to permeate planetary transmission spectra, and possibly derive the relative molecular abundances from the GIARPS observations, placing tight constraints on fundamental proxies of the HJs' formation location and migration history, such as the C/O and O/H ratios.

In the framework of the GAPS project, we observed KELT-9 during four transits of KELT-9 b with the HARPS-N and GIANO-B high-resolution spectrographs in GIARPS configuration (Claudi et al., 2017). The instruments are located at Telescopio Nazionale Galileo (INAF) at the Roque de los Muchachos Observatory, La Palma, Spain. We obtained high-resolution spectra in the wavelength range 390-690 nm and 940-2420 nm. The transit of KELT-9 b lasts 4 hours. The first transit observations were taken with low-cadence sampling with long exposures (600 sec), while for the other three transits we used a higher cadence (300 sec exposures). Fiber A of the spectrograph was centered on the target, and at the same time fiber B was monitoring the sky. During the observations of transits 1 and 2 there was a problem with the atmospheric dispersion corrector (ADC) of the telescope, causing a significant loss of flux, in particular in the blue part of the spectrum. However, final results are valid even when considering only transits 3 and 4, and thus are not affected by the ADC problems.

GAPS Consortium collected a total of 226 spectra bracketing four transits. I excluded from my final transit analysis all the data with a signal-to-noise ratio (SNR) < 70 (as measured in order 46) or taken at airmass > 1.7 , thus discarding 11 of the 226 exposures collected. Adopting the transit ephemerides from Gaudi et al. (2017), I analysed 148 in-transit and 67 out-of-transit exposures.

Regarding KELT-20 system, we have observed two transits with the HARPS-N spectrograph, on 26 August 2019 and 02 September 2019, with an exposure time of 600 s.

Moreover, there were three transits available in the TNG database. The first and second transit were observed 16 August 2017 and 12 July 2018, with an exposure time of 200 s, while for the third transit (19 July 2019) the exposure time was increased to 300 s, to obtain a higher signal to noise ratio. The raw spectra were reduced using the HARPS Data Reduction Software (DRS) which interpolates the extracted spectra on a uniform grid with a spacing of 0.01 Å.

I used HARPS-N datasets collected by GAPS group to develop my own tools to analyze high-resolution exoplanetary spectra. The goal is becoming able to detect weak spectral lines, paving the way to the biosignatures detection in the high-

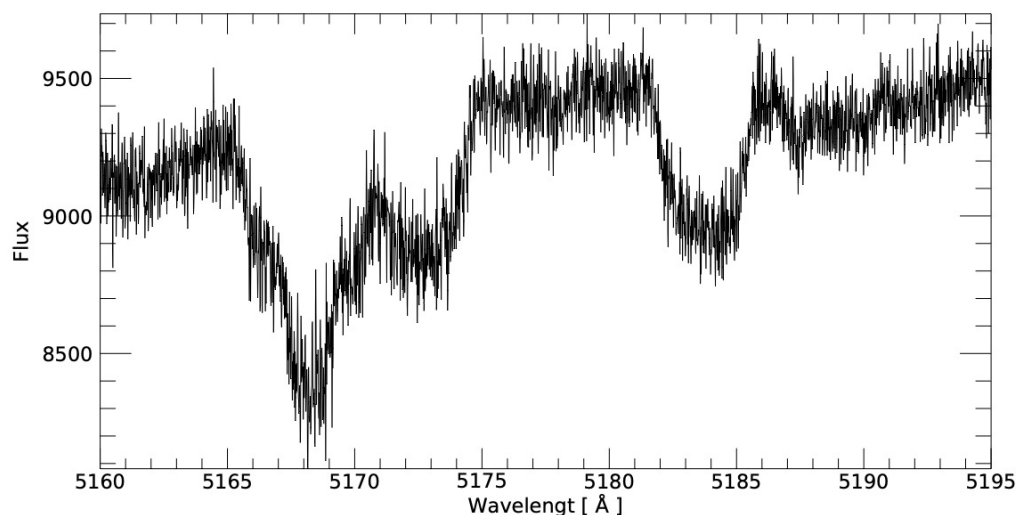


Fig. 7.1.: KELT-9 spectrum in the region between 5155.0 and 5200 Å, taken on the 10 June 2018 night. The bluer part of the spectrum is affected by the ADC problem, but the spectra are not affected enough to invalidate my analysis.

resolution transmission spectra of exoplanets. In particular, for the development of my tools I focused on the Mg I triplet whose lines can be observed at 5167.3 Å, 5172.7 Å, and 5183.6 Å. I will describe the steps I took for the analysis in the region of the spectrum between 5155.0 and 5200 Å, but it can easily be applied to different regions for the study and detection of other elements.

Figure 7.1 shows an example of KELT-9 star spectrum in the region considered for the analysis. The planet transmission spectrum is blended into the signal and several steps are required in order to retrieve it.

7.3 Telluric Correction

The correction of absorption lines from the stellar photosphere as well as the Earth's atmosphere (telluric lines) is mandatory for visible and infrared observed stellar and transmission spectra. Earth's atmosphere's elements like OH, O₂, O₃, CO₂, CH₄, CO, N₂O, H₂O, and chlorofluorocarbons (CFC) molecules create absorption bands in the visible and primarily in the IR (see Fig.7.2).

Telluric lines correction is crucial to reach the goals fixed by the small signals in transmission spectroscopy. In the optical domain, the lines of the two most interesting elements for transmission spectroscopy (NaI D doublet and H α) are polluted by the water transitions in terrestrial atmosphere. Moreover, in the attempt of detecting molecules such as H₂O, CO, and O₂ in the exoplanet atmospheres, it

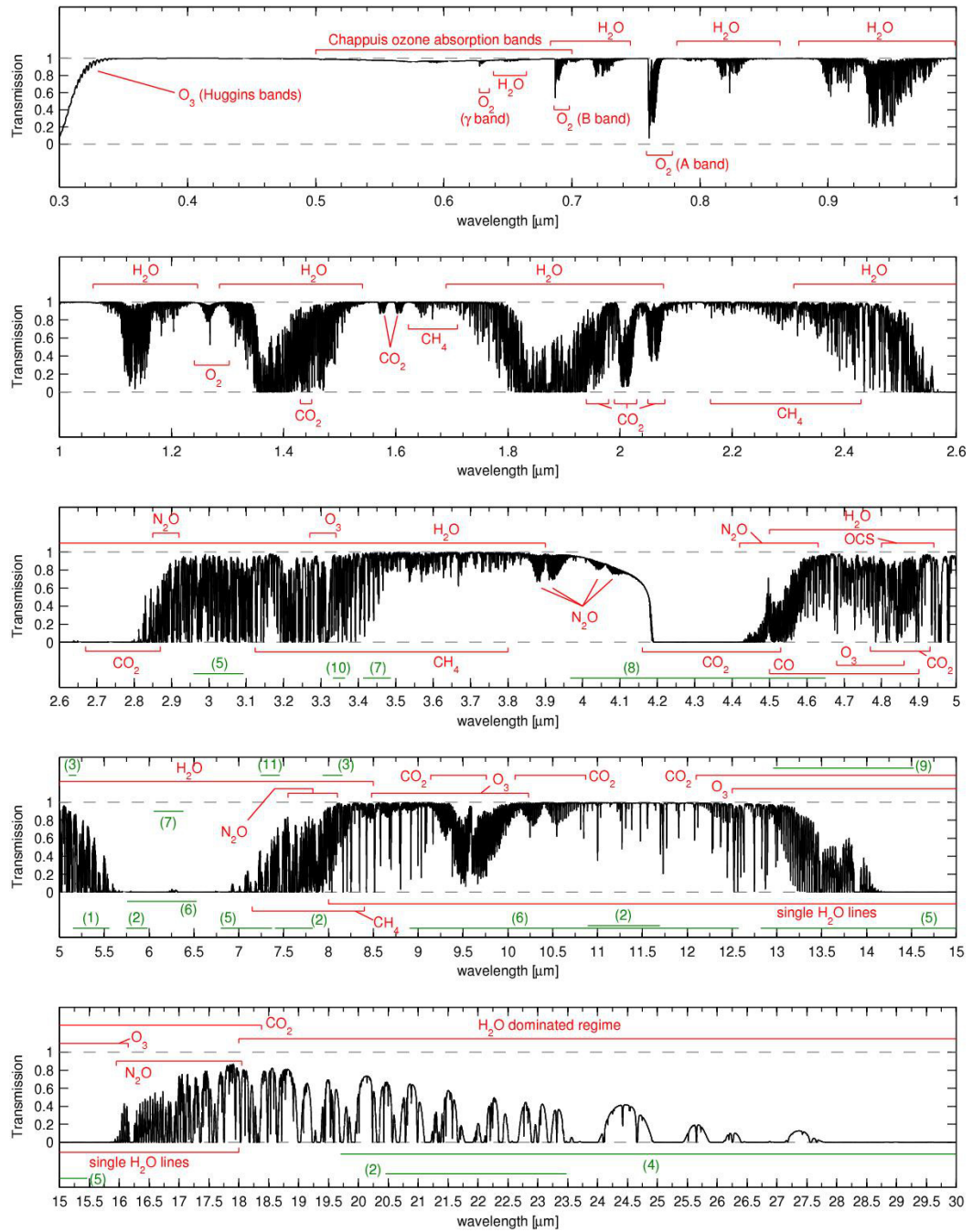


Fig. 7.2.: Synthetic absorption spectrum of the sky between 0.3 and 30 μm (resolution $\mathcal{R} \sim 10,000$). The eight main molecules contribute more than 5% to the absorption in some wavelength regimes. Image from Smette et al. (2015).

is necessary to be sure that the potential exoplanetary signatures do not belong to terrestrial atmosphere (Snellen et al., 2010; Snellen et al., 2013; Rodler and López-Morales, 2014; Birkby et al., 2017; Allart et al., 2017).

Telluric lines have different properties. If absorption lines are not saturated, their contrast depends on the airmass and on water column variations in the air. The lines intensity also depends on the molecule abundance along the line of sight. In terrestrial reference frame, the position of telluric lines is stable, while they change position during the night or from one night to another with respect to the stellar spectra due to Earth's rotation. It is also worth noting that some telluric lines can be observed not only in absorption, but also in emission. That is the case of telluric sodium, that undergoes seasonal variations and possibly does not follow the water absorption levels.

In practice, different methods for telluric lines correction in absorption can be used. The common idea is creating a high quality reference spectrum similar to the one impressed in the scientific target. This allows to correct the scientific spectra for telluric pollution by dividing them by the telluric reference spectrum. In the next Paragraphs, I will describe the two most used methods for the correction of telluric features in transmission spectroscopy.

7.3.1 Empirical Extraction of the Telluric Spectrum

This method was described in Vidal-Madjar et al. (2010) and Astudillo-Defru and Rojo (2013), and used in several works such as, for example, Wyttenbach et al. (2015). It was implemented using the airmass in the radiative transfer equation. As a consequence of the usual hypothesis of a radiative transfer in a plane parallel atmosphere and assuming only absorption, the solution of the equation is given by

$$\ln I/I_0 = NK_\lambda s \quad (7.1)$$

where I is the intensity at certain wavelength λ , I_0 is the source intensity, Nk_λ is the optical depth at zenith and s is the airmass.

The zenithal optical depth is derived at each wavelength through a linear regression to $\ln(I)$ as a function of the airmass s at a mid-exposure. This procedure was done only using out-of-transit spectra in order not to over-correct for the possible exoplanet atmosphere we are looking for. This method yields for each night a reference telluric spectrum such as

$$T(\lambda) = T^1(\lambda) \equiv e^{N \cdot K_\lambda} \quad (7.2)$$

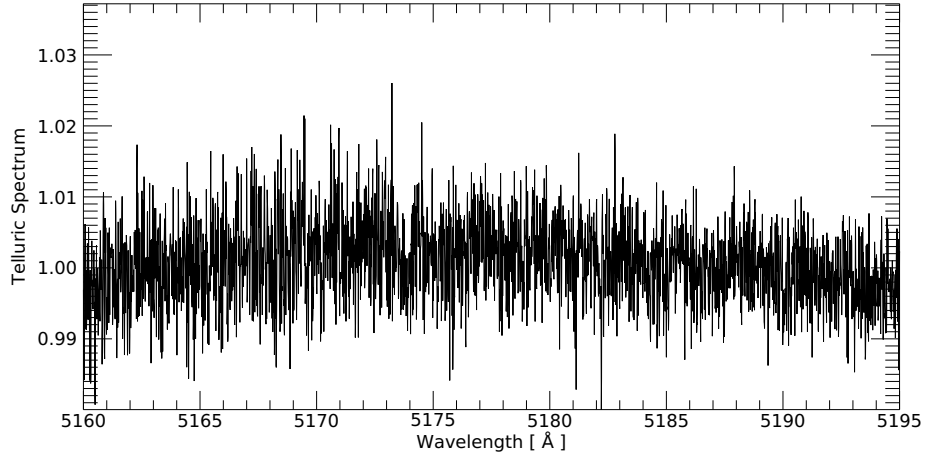


Fig. 7.3.: Empirical telluric spectrum of the 10 June 2018 night.

corresponding to a zenithal atmospheric transmission. By taking advantage of the relation between the telluric line strength and the airmass and rescaling all spectra as if they have been observed at the same airmass, it is possible to correct the spectra for telluric contamination. To obtain the rescaled spectra $F_{ref}(\lambda)$ at the average airmass s_{ref} of the in-transit spectra, the observed spectra $O_s(\lambda)$ are simply divided by the telluric reference spectrum to the power $s - s_{ref}$:

$$F_{ref}(\lambda) = O_s(\lambda) / e^{N \cdot K_\lambda \cdot (s - s_{ref})} \quad (7.3)$$

If the quality and the stability of the observation during nights are good enough, this method is sufficient to correct down to the statistical noise level. The quality of the nights are generally not sufficient as second-order variations of telluric lines are present, leaving telluric residual still visible in transmission spectra. Then, in some cases, it is necessary to apply a second telluric correction. Both the transmission spectra and the telluric spectra are correlated, since they contain telluric features at corresponding wavelengths. The transmission spectrum is then divided by a linear fit between all corresponding fluxes in wavelength of the transmission spectrum and the telluric reference spectrum.

Figure 7.3 shows the empirical telluric spectrum of the first night of observation. The ADC problem affects also the Earth's atmosphere spectrum, that appears slightly curved. However, in the spectral region considered, I did not use this correction, since the intensity of the telluric lines is comparable with the strength of the signal and its subtraction would just result in adding statistical noise to the spectrum.

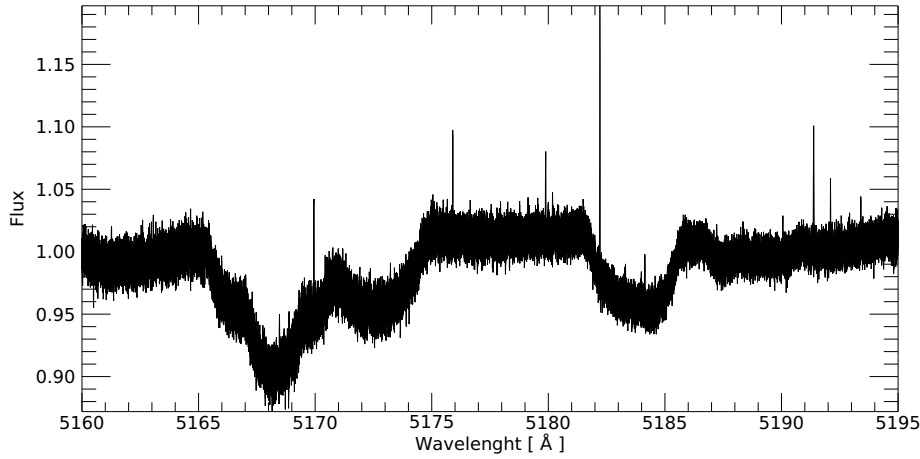


Fig. 7.4.: Normalized KELT-9 spectrum in the region between 5155.0 and 5200 Å.

7.3.2 Theoretical Models for Telluric Correction

Another method makes use of telluric models such as **TAPAS** (Bertaux et al., 2014) or **Molecfit** (Smette et al., 2015) for transmission spectra correction. **Molecfit**, the most used tool to create telluric models for transmission spectroscopy, uses a line-by-line radiative transfer model (LBLRTM) to create a telluric spectrum at a very high resolution ($\mathcal{R} \sim 4,000,000$). This tool requires an atmospheric profile that describes temperature, pressure, humidity and abundance of molecular species as a function of altitude for a given observatory site at one particular time and at a given airmass.

Before the correction, the model spectrum needs to be fitted to the observed spectrum by adjusting the continuum, the wavelength calibration and the instrumental resolution, and this results to be crucial to derive precise transmission models (e.g., Allart et al., 2017). The modelling regions have to be selected by hand to not only avoid stellar features, but also to find telluric lines above the noise level.

7.4 Transmission Spectrum

The analysis of the observed spectral series during a transit has one goal, the extraction of the exoplanetary atmospheric signal. In particular, transmission spectroscopy uses differential methods to extract the transmitted signal. Ground-based transit spectroscopy is a double-differential technique. First of all, a spectral

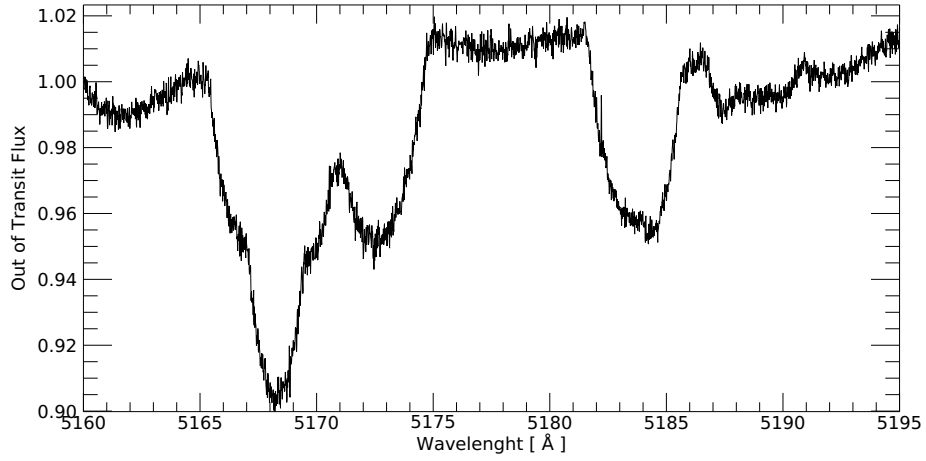


Fig. 7.5.: Mean out-of-transit spectrum. The stellar spectra taken before and after the transit are used to construct this mean star spectrum.

differentiation is required, because of time-correlated noises introduced by the variations in the Earth atmosphere. This normalization is carried out in two steps. First, I chose in the stellar spectra continuum values in two different wavelength bands, far away from the Mg I line cores, and performed a linear fit between them. I completed the differentiation by dividing the stellar spectra by the linear fit (Fig. 7.4). Following Wyttenbach et al. (2017), each spectrum is divided by a mean out-of-transit spectrum (i.e. the mean star spectrum, Fig. 7.5) to obtain a transmission spectrum in which supplementary absorption due to the exoplanetary atmosphere are measurable. Transmission spectroscopy measures the spectral ratio $\mathcal{R}'(\lambda) = \mathcal{R}(\lambda) - 1$ defined by Brown (2001) as

$$\mathcal{R}'(\lambda) = \frac{F_{\text{in}}(\lambda) - F_{\text{out}}(\lambda)}{F_{\text{out}}(\lambda)} \quad (7.4)$$

where $F_{\text{in}}(\lambda)$ is the in-transit spectrum and $F_{\text{out}}(\lambda)$ is the out-of-transit spectrum. It is worth noting in Fig. 7.5 that the spectrum is not perfectly normalized, but as the same normalization is applied to all the spectra, when the in-transit spectrum is divided by the mean out-of-transit the result is fixed and I obtain a perfectly normalized spectrum.

Then, a temporal differentiation is required: out-of-transit observations contain the stellar light absorbed by the terrestrial atmosphere, while observations during transit additionally contain the exoplanet atmosphere transmitted light diluted into the stellar flux. During a transit, the planet's orbital movement impresses a Doppler shift on the absorption lines of the atmosphere. Hence, the lines measured

in transmission are typically RV shifted with respect to the center of the stellar lines of 10-20 km s⁻¹. I extracted the transit spectrum by coadding the shifted spectral ratios obtained at each time step during the transit

$$\tilde{\mathcal{R}}(\lambda) = \sum_{t \in \text{in}} \frac{\tilde{f}(\lambda, t)}{\tilde{F}_{\text{out}}(\lambda)} \Big|_p \quad (7.5)$$

where the $\sim$ symbol indicates that the spectra are normalized and the $|_p$ designs the correction for the planetary RV shift. Transit spectroscopy measures the spectral ratio (Eq. 7.4). It is worth noting that the use of ground-based spectrographs makes normalization a necessary process, but it erases the main component of the spectral ratio, the one due to the solid disk of the planet. Moreover, the spectral normalization preserves the signatures of the planetary atmosphere appearing during the transit, at the cost of correcting out for the “white light” transit signal and only revealing radius variations from differential absorption signatures in the planet atmosphere.

7.4.1 Doppler Tomography

The technique of Doppler tomography, developed by Marsh and Horne (1998) to study close-binary systems, aims to recover a model-independent map that resolves the distribution of line emission and/or absorption within the binary using a time-series of spectra. In essence, the orbiting body traces out a sinusoidal radial velocity curve of the form

$$v_R(\phi) = \gamma v_x \cos 2\pi\phi + v v_y \sin 2\pi\phi \quad (7.6)$$

where ϕ is the orbital phase, γ is the systemic velocity of the system, and v_x and v_y are the radial velocity semi-amplitudes of the cosine and sine terms, respectively. From this analysis it is possible then to use the information encoded in line-profiles observed as a function of orbital phase, calculating the strength of the line emission (or absorption) as a function of velocity. The final result is a map of the orbiting material in velocity space, defined as the strength of the line emission (or absorption) as a function of velocity.

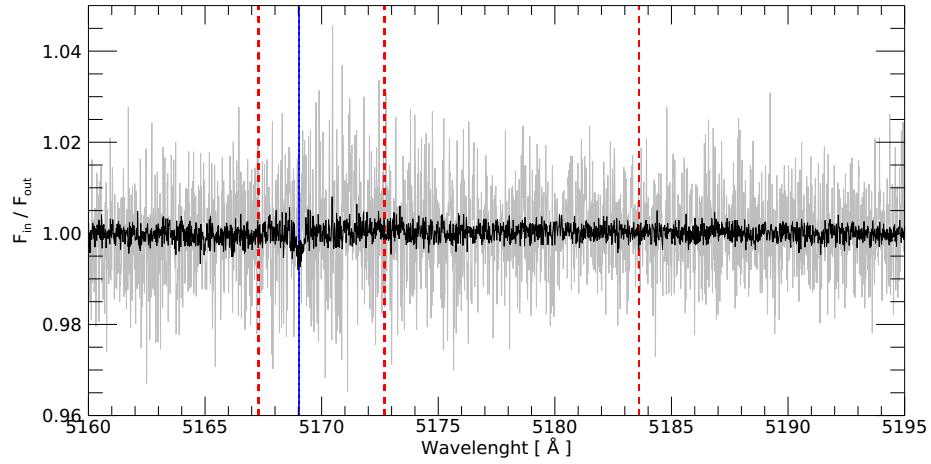


Fig. 7.6.: KELT-9 b's transmission spectrum for the first transit. For a single transit, there is no evidence of Mg I triplet absorption (red dashed lines), but there is trace of the Fe II line at 5169.03 Å (solid blue line).

7.4.2 Results for the Mg I Triplet

I focused on the transitions of the magnesium triplet (5167.32 Å, 5172.68 Å, and 5183.60 Å) and then applied the same tool to other lines. The systemic velocity of the system is -19.82 km s^{-1} . Moreover, during a transit, the orbital movement of the planet impresses a Doppler shift on the absorption lines of the planetary atmosphere. Then, it is mandatory to take it into account these shifts, in order to obtain the correct signals. The transmission spectra obtained for each night are therefore shifted for the systemic velocity and for the correspondent velocity of the planet at any instant of the transit. I obtained the individual transmission spectra (Fig. 7.6) in the planetary reference frame and I co-added them in order to achieve a higher signal-to-noise ratio (Fig. 7.7).

Figure 7.8 shows the tomography of the transmission spectrum of KELT-9 b in the wavelength space. No strong absorption of the magnesium triplet can be seen on the single lines. The vertical blue traces show the absorption in the planet reference frame, while the red oblique traces are due to the stellar effects (center-to-limb variations and stellar rotation, e.g. Borsa and Zannoni, 2018). The validity of the analysis is confirmed by the absorption line at 5169.03 Å, a Fe II line, element known to be present in the atmosphere of the planet (Hoeijmakers et al., 2018). I also conducted my analysis on other lines, in order to have a clearer view on the atmospheric composition of KELT-9 b.

A summary of the absorption lines detected in the planetary atmosphere is reported

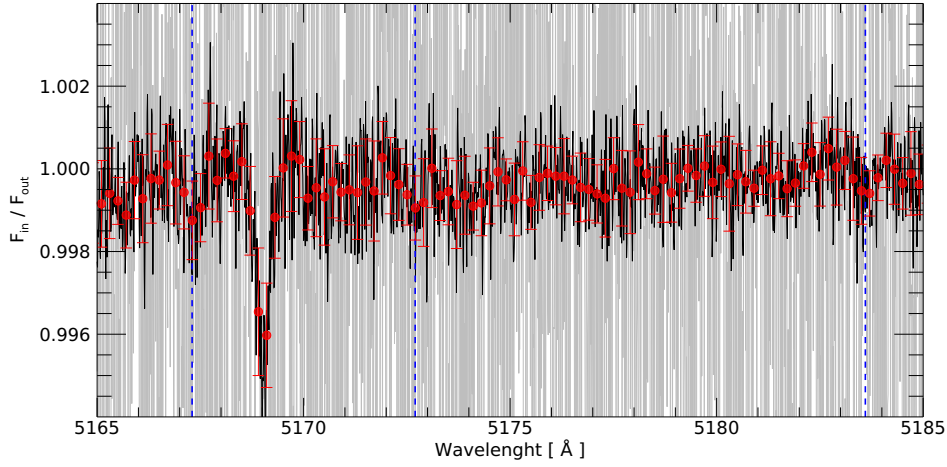


Fig. 7.7.: KELT-9 b's transmission spectrum for the four transits. The presence of Mg I triplet lines is slightly more noticeable, but there is no clear evidence, while the Fe II absorption signal at 5169.03 Å becomes stronger.

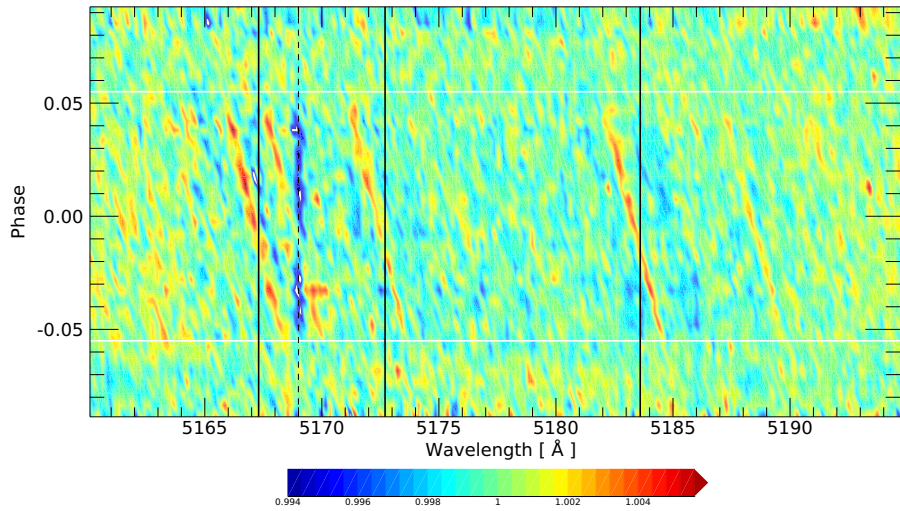


Fig. 7.8.: Tomography of the absorption lines after analyzing four transits of KELT-9 b. The white solid lines indicate the ingress and the egress of the transit. The blue vertical traces represent the planetary absorption, while the red oblique trace is due to stellar effects. The solid black lines show the Mg I triplet lines and no strong absorption can be seen in the colored map. The Fe II line at 5169.03 Å is clearly visible.

Tab. 7.2.: Summary of the detections in the transmission spectra of the four transits of KELT-9 b. Detection is considered positive (Y) only at the level of 4σ and beyond, and partial (YN) above 3σ . “2D” refers to the visibility in the 2D tomographic map.

Element	$\lambda_{\text{air}} [\text{\AA}]$	Contrast [%]	FWHM [km s^{-1}]	Shift [km s^{-1}]	Detection	2D
Wavelength Space						
H β	4861.33	-0.493 ± 0.034	34.4 ± 2.7	2.6 ± 1.1	Y	Y
Mg I	5167.32	N/A	N/A	N/A	N	Y
Fe II	5169.03	-0.441 ± 0.023	21.54 ± 1.38	-0.27 ± 0.56	Y	Y
Mg I	5172.68	N/A	N/A	N/A	N	Y
Mg I	5183.60	N/A	N/A	N/A	N	Y
Na D2	5889.95	-0.437 ± 0.096	32.37 ± 5.65	-0.48 ± 2.17	Y	Y
Na D1	5895.92	-0.232 ± 0.054	5.05 ± 0.47	4.86 ± 1.12	Y	Y
H α	6562.81	-0.857 ± 0.031	41.48 ± 1.91	1.72 ± 0.77	Y	Y
Velocity Space						
Mg I	Triplet Sum	-0.084 ± 0.022	23.76 ± 11.42	-0.37 ± 3.74	YN	Y
Mg I	5 Lines Sum	-0.084 ± 0.026	24.84 ± 11.44	-0.77 ± 4.74	YN	Y

in Table 7.2. The parameters are calculated with a Gaussian fit. The Mg triplet is detected only when averaging the three lines in the velocity space, as described in Paragraph 7.4.3.

7.4.3 Increasing the Intensity of Weak Signals

The wavelength at which Mg I triplet absorbs light here on Earth is known and it is given by the three lines I mentioned in the previous Sections (5167.3 $\text{\AA}$, 5172.7 $\text{\AA}$, and 5183.6 $\text{\AA}$). In order to achieve a higher signal-to-noise ratio, I decided to co-add the three lines. To do that, it is necessary to turn the reference frame from wavelength to radial velocities space. I took the three lines separately, setting each line center to zero, and obtain the velocity of each spectral line using the following Equation:

$$v_{\text{line}} = \frac{\lambda - \lambda_{\text{rest}}}{\lambda} \cdot c \quad (7.7)$$

where c is the speed of light, and λ_{rest} is the wavelength of the line of reference. Having all the lines in the velocities reference frame, allowed me to co-add them, with the result that the magnesium signature becomes more evident. Figure 7.9 shows the tomography of my analysis, after co-adding the three Mg I lines of the triplet. The vertical blue absorption trace around 0 km s^{-1} becomes more evident. It also becomes evident that the velocity of magnesium in the atmosphere of KELT-9 b changes from ~ -24 to $\sim 24 \text{ km s}^{-1}$, pointing out an expansion of the atmosphere probably due to the atmospheric escape caused by the star-planet interaction processes.

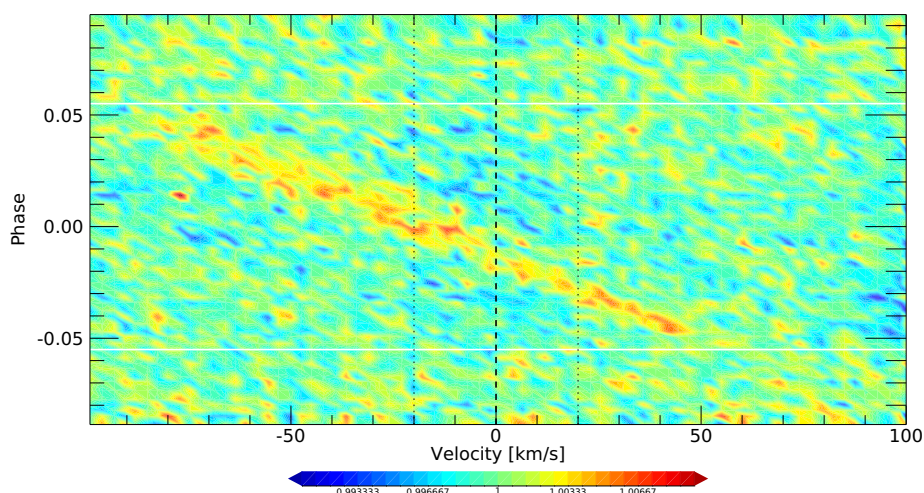


Fig. 7.9.: Tomography after co-adding the three lines in the velocities reference frame. The white solid lines indicate the ingress and the egress of the transits. The dashed black line shows where we expect to find the Mg trace in the planetary restframe (i.e. 0 km s^{-1}). The pointed black lines show the enlargement of the trace.

7.4.4 Magnesium Lines: the More the Merrier?

The Mg I has other lines in the transmission spectrum that can be analyzed. I looked for the strongest Mg I lines in the NIST Atomic Spectra Database¹ and I found three lines with an intensity comparable with the MgI triplet: 4702.9 Å, 5528.4 Å, and 5711.1 Å.

I repeated the analysis described in the previous Paragraphs, in order to obtain KELT-9 b's transmission spectrum in small wavelength intervals containing the new lines. Again, I chose to use short intervals in order to minimize the time for computation.

From the analysis for the line at 4702.9 Å, I obtained a transmission spectrum more noisy, probably due to the fact that this line is in the bluer part of the spectrum, where HARPS-N is less efficient, so I decided not to use it further. Instead, I kept the analysis for the other two lines and I co-added all the transmission spectra in the radial velocity space. Figure 7.10 shows the comparison between the Mg I triplet transmission spectrum and the transmission spectrum with all the five lines co-added. From the plot, it is clear that adding two more lines to the analysis does not significantly increase the signal-to-noise. More details can be found in Table 7.2

¹<https://physics.nist.gov>

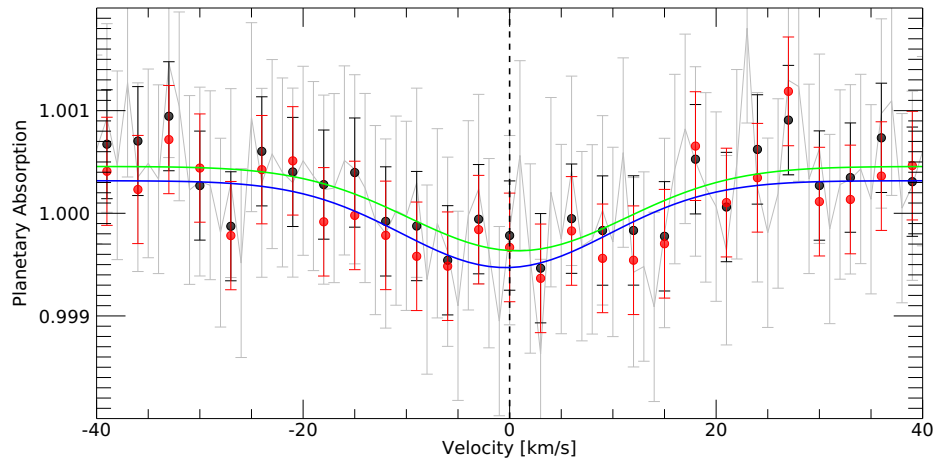


Fig. 7.10.: Transmission spectrum of KELT-9 b in the radial velocities space, where the co-added absorption lines of Mg I are centered at 0 km/s. The red dots show the co-added spectrum for the Mg I triplet; the black dots show instead the co-added spectrum for the Mg I triplet and the lines at 5528.4 and 5711.1 Å. The blue line is the Gaussian fit for the Mg triplet, the green line is the fit for the five lines.

7.5 Analysis of Other Planets: the Case of KELT-20 b

The tool I developed works well in Mg I detection and can be easily applied to find other elements in the transmission spectra of exoplanets.

I used the same tool to analyze the atmosphere of other planets included in the list of planets observed by GAPS Consortium. A particular case of interest is represented by MASCARA-2 b/KELT-20 b.

Figure 7.11 shows the tomography and the transmission spectrum of the Mg I triplet. The absorption lines of the triplet can be distinguished more easily than for KELT-9 b. Also the Fe II absorption line at 5169.03 Å, used to check the validity of the analysis, is clearly visible. Figure 7.12 shows the tomography of the absorption lines of the Mg I triplet co-added in the radial velocity reference frame. Here the broadening of the Mg I absorption is not as large as for KELT-9 b, probably due to the fact that the temperature of this planet is inferior to that of KELT-9 b. As for KELT-9 b, the analysis on the single lines was amplified on other elements, in order to have a clearer view on the atmospheric composition of the planet.

A summary of the absorption lines detected is reported in Table 7.3. The parameters are calculated with a Gaussian fit. In this case, two lines of the Mg I triplet are detected also from the basic analysis. I also analyzed the presence of other elements such as oxygen, sulfur, and phosphorus, but my tool was not able to find any trace

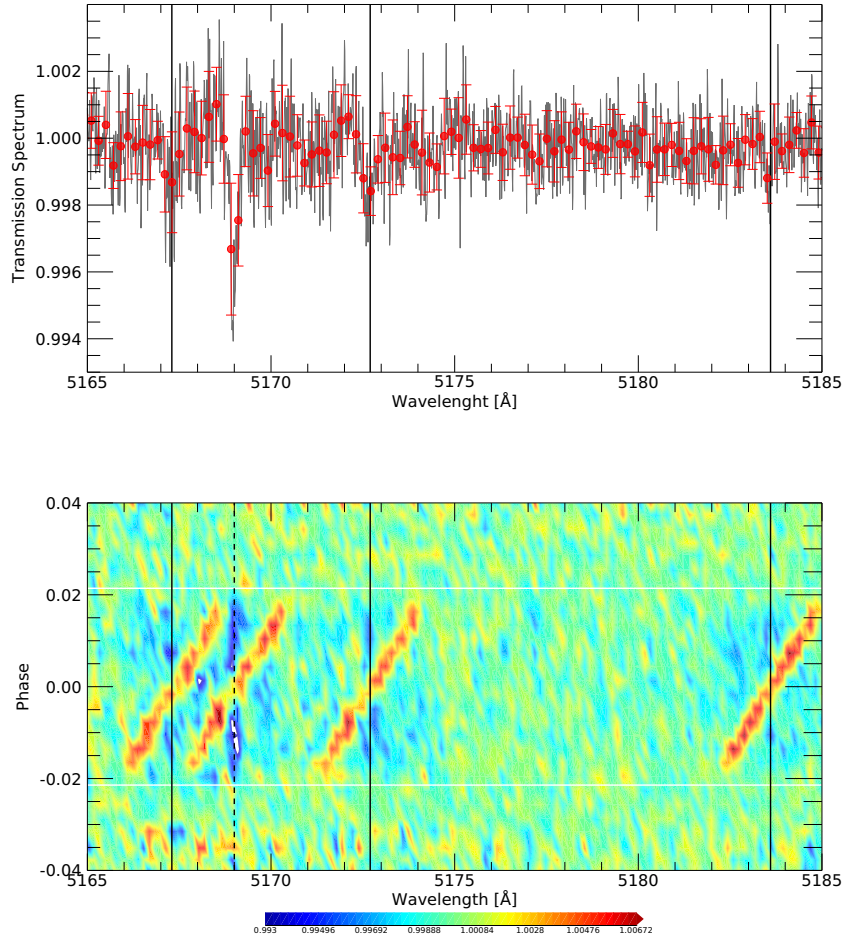


Fig. 7.11: *Top panel:* Transmission spectrum of KELT-20 b in the wavelength space. The Mg I triplet absorption lines are more evident than for KELT-9 b. *Bottom panel:* Absorption lines tomography of KELT-20 b in the wavelength space. The horizontal white lines show the ingress and egress of transit. The doppler shadow of the planet (red) and the planetary atmosphere track (blue) are both evident. The vertical solid black lines show the position of Mg I triplet lines, while the dashed black line shows the position of the Fe II absorption line.

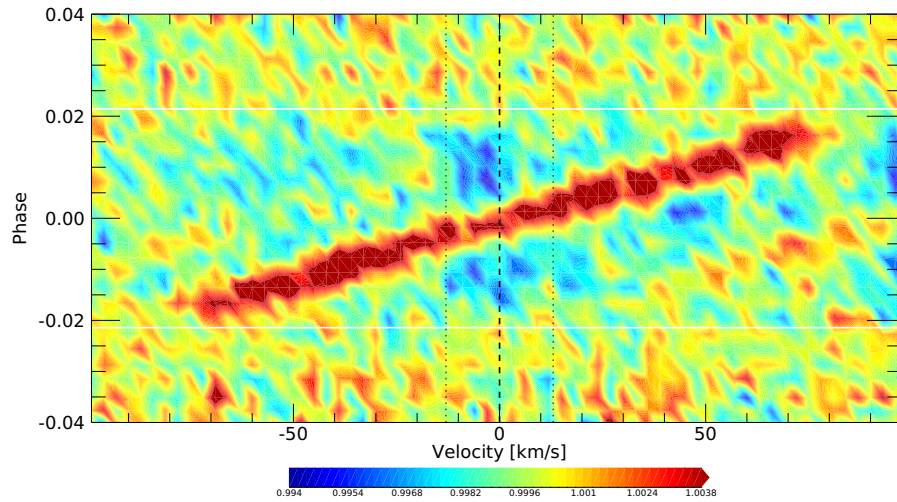


Fig. 7.12.: Tomography after co-adding the three lines in the velocities reference frame. The white solid lines indicate the ingress and the egress of the transits. The dashed black line shows where we expect to find the Mg trace in the planetary restframe (i.e. 0 km s^{-1}). The pointed black lines show the enlargement of the trace.

of these elements. However, their presence can not be completely excluded as their signal could be hidden in the noise, therefore the results are not reported in Table 7.3.

I presented the results of my analysis at the 15th GAPS Progress Meeting, held in Catania from 4 to 6 December 2019.

Figure 7.13 shows the comparison between the Mg I triplet transmission spectrum and the transmission spectrum with all the five lines co-added for KELT-20 b.

Again from the plot, it is clear that adding two more lines to the analysis does not significantly increase the signal-to-noise, but it makes the detection slightly less evident because more noise is added to the final transmission spectrum.

7.6 Cross-Correlation

The high dispersion of a high-resolution spectrograph means that the number of photons obtained per spectral element is limited. Typically, the individual absorption lines are embedded in the photon noise of the much brighter star. Cross-correlation techniques can be used to match a model template spectrum to the observed spectrum to extract the planet spectrum from the noise. The cross-correlation

Tab. 7.3.: Summary of the detections in the transmission spectra of the four transits of KELT-20 b. Detection is considered positive (Y) only at the level of 4σ and beyond, and partial (YN) above 3σ . “2D” refers to the visibility in the 2D tomographic map.

Element	$\lambda_{\text{air}} [\text{\AA}]$	Contrast [%]	FWHM [km s^{-1}]	Shift [km s^{-1}]	Detection	2D
Wavelength Space						
H β	4861.33	-0.421 ± 0.042	25.69 ± 3.20	-6.70 ± 1.33	Y	Y
Mg I	5167.32	-0.166 ± 0.028	14.39 ± 4.11	-4.81 ± 1.70	Y	Y
Fe II	5169.03	-0.544 ± 0.035	11.6 ± 0.90	-2.72 ± 0.37	Y	Y
Mg I	5172.68	-0.193 ± 0.031	16.78 ± 2.76	0.88 ± 1.15	Y	Y
Mg I	5183.60	N/A	N/A	N/A	N	Y
Na D2	5889.95	-0.424 ± 0.036	15.8 ± 1.53	-3.72 ± 0.63	Y	Y
Na D1	5895.92	-0.415 ± 0.037	13.83 ± 1.44	-2.41 ± 0.59	Y	Y
H α	6562.81	-0.626 ± 0.048	24.28 ± 2.74	-3.11 ± 1.12	Y	Y
Velocity Space						
Mg I	Triplet Sum	-0.163 ± 0.035	15.28 ± 4.05	-3.15 ± 1.61	Y	Y
Mg I	5 Lines Sum	-0.145 ± 0.036	15.50 ± 4.53	-3.46 ± 1.81	Y	Y

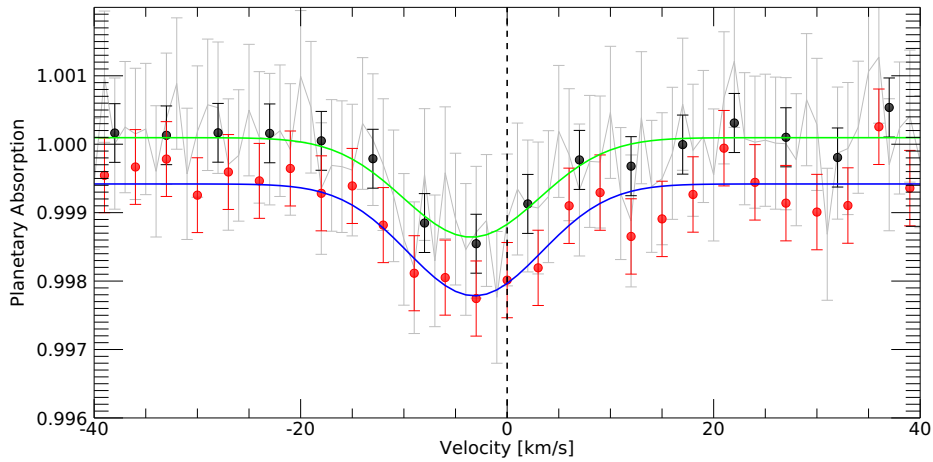


Fig. 7.13.: Transmission spectrum of KELT-20 b in the radial velocities space, where the co-added absorption lines of Mg I are centered at 0 km/s. The red dots show the co-added spectrum for the Mg I triplet; the black dots show instead the co-added spectrum for the Mg I triplet and the lines at 5528.4 and 5711.1 Å. The blue line is the Gaussian fit for the Mg I triplet, the green line is the fit for the five lines.

$C(x, y)$ effectively measures the degree of similarity between a spectral template and the noisy data:

$$C(x, y) = \frac{\sum_{k=0}^N (x_k - \bar{x}) \cdot (y_k - \bar{y})}{\sqrt{\sum_{k=0}^N (x_k - \bar{x})^2 \cdot \sum_{k=0}^{N-1} (y_k - \bar{y})^2}} \quad (7.8)$$

The cross-correlation $C(x, y)$ varies between 1.0 (maximum correlation) and -1.0 (anti-correlation) and is calculated for a range of radial velocity shifts of the template x . This yields the cross-correlation function $CCF(x, y, v)$, which measures the degree of overlap between the template and the data as a function of radial velocity v . When the template is shifted to the same radial velocity as the data, the CCF peaks and effectively co-adds all the absorption lines that are present in both the template and the data. This integration of the spectrum averages out the photon noise present at each spectral line, allowing the template spectrum to be detected even if the photon noise is stronger than the individual absorption lines.

The position of the cross-correlation peak in velocity space corresponds to the Doppler shift of the target spectrum at the time of the observations. Therefore, the CCF can be used to precisely measure the radial velocity of a target object. This technique has been previously used to detect molecular absorption by CO and H₂O in the day side emission spectra of a number of hot Jupiters (e.g., Snellen et al., 2010; Brogi et al., 2012; Birkby et al., 2017) and more recently for the spectral survey of metallic elements in the atmosphere of ultra-hot Jupiters (e.g., Hoeijmakers et al., 2019).

During the third year, I developed a tool for the cross-correlation of the transmission spectra with template spectra of metallic elements, in order to obtain the detection of elements in the atmospheric spectrum. In the following Paragraphs, I present the analysis of KELT-20 b atmosphere using cross-correlation. Some of the results of my analysis have been included in a paper (Rainer et al., 2021), submitted to a peer-reviewed journal.

7.6.1 Spectra Reduction for Cross-Correlation Analysis

HARPS-N spectral wavelength coverage lies between 3900 and 6900 Å. I run the analysis on the whole one-dimensional spectrum using as initial steps the ones I showed in the previous Sections.

First, I normalized each spectrum. I constructed a cubic spline function for the spectrum, subdividing it into smaller portions and then I completed the normalization by dividing the stellar spectra by the spline function curve. Second, I used the

empirical method for the correction of the telluric lines. I divided each observed spectrum by the telluric reference spectrum, following the same steps illustrated in Section 7.3.1. Third, I created the stellar profile by averaging the out-of-transit spectra. Last, I isolated the signature of the planet by dividing each spectrum for the stellar profile, obtaining the transmission spectrum in the whole wavelength range of HARPS-N.

7.6.2 Mask Templates for Cross-Correlation

To compute the cross-correlation function, a mask is needed that defines the weights by which spectral pixels are co-added. As a first approximation, I used the masks for each species constructed by Hoeijmakers et al. (2019) through the forward modeling of the transmission spectrum of KELT-9 b. KELT-9 b and KELT-20 b are similar for temperature, size, and distance from the host star, therefore I assumed that their atmospheres are alike. In their paper, Hoeijmakers et al. (2019) assume elemental abundances equal to solar metallicity and an isothermal profile of 4,000 K between pressures of 10 bar to 10^{-15} bar. At this temperature, the abundances of molecules are low and atoms are partially ionized. The model spectra of these species are also convolved with a Gaussian kernel with a FWHM width of 0.8 km s^{-1} to match the approximate wavelength sampling of HARPS-N. To create the Fe I model used for the paper (Rainer, ..., Frustagli et al., 2021), we employed the $\pi\eta$ line-by-line radiative transfer code (Pino et al., 2018), a code already applied for the simultaneous interpretation of ground-based, optical, high spectral resolution observations with HARPS and HST WFC3 observations (Pino et al., 2018) and updated for the purposes this paper ².

Figure 7.14 shows one of the Fe I masks used for the cross-correlation analysis in Rainer et al. 2021. This mask is created assuming equilibrium chemistry in the atmosphere of the planet and a temperature of 3,000 K.

7.6.3 Cross-correlation of the Transmission Spectrum with the Different Masks

The planet's potential absorption features were extracted by cross-correlating the residual spectra with the template spectra across the full wavelength range of the data. Subsequently, I aligned and combined all the cross-correlation functions, assuming a range of values for the maximum orbital radial velocity of the planet,

²See Rainer, ..., Frustagli et al., 2021 for a full description of the masks

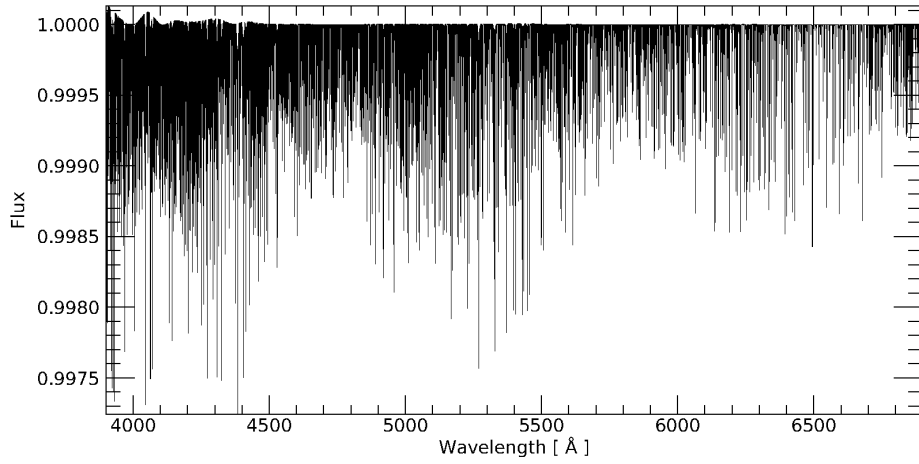


Fig. 7.14.: Sample of model spectra of Fe I, assuming an isothermal atmosphere at 3,000 K.

K_p . Figure 7.15 and Figure 7.16 show the cross-correlation functions obtained when cross-correlating the observations of the five nights with the templates for Na I and Fe II from Hoeijmakers et al. (2019) respectively. The behaviour of Fe I will be discussed more in detail in Paragraph 7.6.3.1 The blue diagonal trace is the stellar signal, while the red trace is the absorption from the atmosphere of the planet. The dashed line indicates the expected planetary velocity. I detected significant excess absorption at the rest-frame velocity of the planet in the cross-correlation functions of Na I, Fe I, and Fe II, confirming previous detections (e.g., Casasayas-Barris et al., 2019; Nugroho et al., 2020; Stangret et al., 2020b), and additionally I found an evidence for the presence of Mg I in the atmosphere of the planet (see Fig. 7.17). In Table 7.4 I present a summary of the detections in the five transits of KELT-20 b. The same detections have also been confirmed by Hoeijmakers et al. (2020). Particularly interesting is the fact that in this planet I could not find any trace of other elements such as Sc II, Y II and Cr II that were present instead in the atmosphere of KELT-9 b. To explain this discrepancy, it is worth noting that there is a huge difference in equilibrium temperature of almost 2,000 K between the two planets, so it is plausible that significant differences exist between the atmospheric chemistry and thermal structure of the atmospheres of these two planets. A direct consequence of this is the fact that the masks used for KELT-9 b are just a good first approximation as a template for cross-correlation and more specific models are needed in order to retrieve the elements that are missing. Another interesting fact is that the peak locations of the CCF features generally suggest a blueshift of ~ -1 to -10 km s^{-1} , which might be indicative of systematic errors in the determination of the systemic velocity, which can be difficult to constrain for fast-rotators, or since

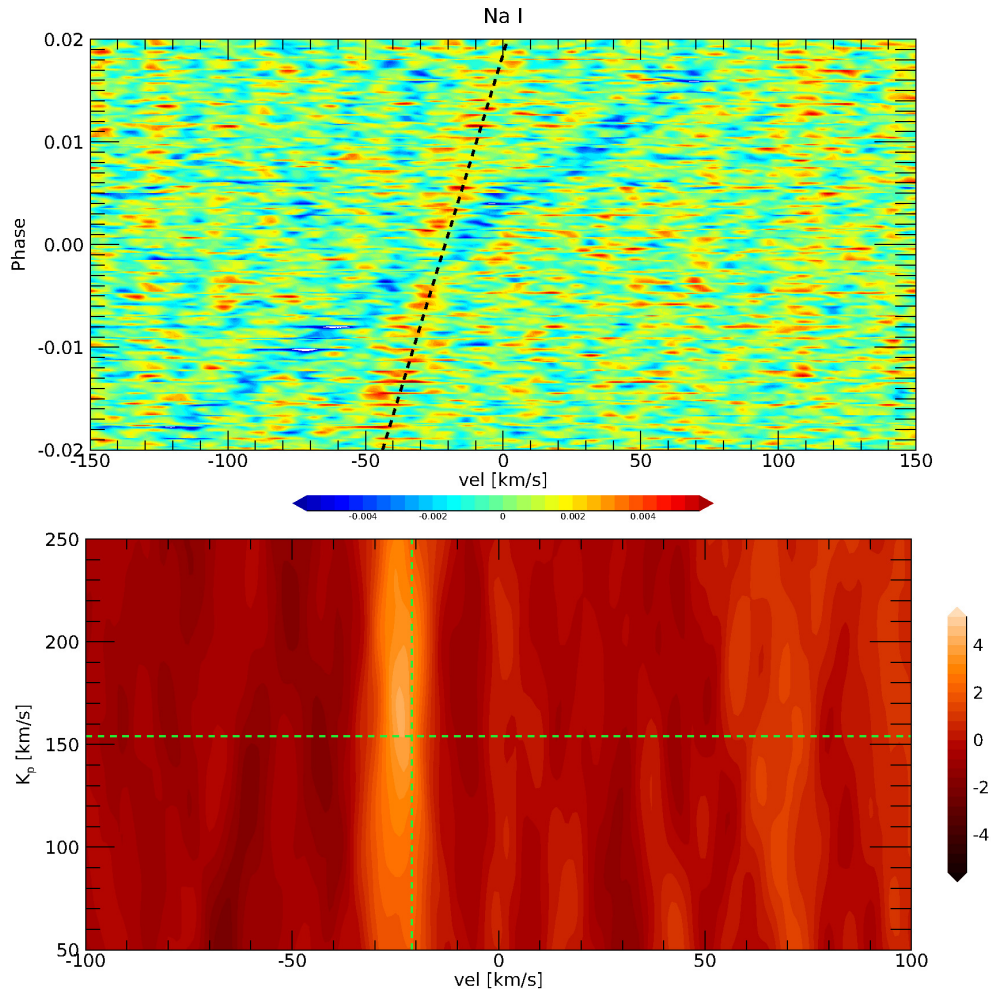


Fig. 7.15.: Cross-correlation of the data with the Na I model. The top panel shows the contour plot of the temporal variation of the cross-correlation, with a dashed line to show the expected planetary velocity; the colorbar scale is in ppm. The bottom panel is the K_p vs velocity map after summing the cross-correlations for different K_p , with colorbar scale in S/N. Green dashed lines are centered on the expected planetary position.

Tab. 7.4.: Summary of cross-correlation detections in the atmosphere of KELT-20 b. Center and S/N are estimated for uniformity at the theoretical K_p value. The significance of the detections was calculated by dividing the best K_p cross-correlation function for the noise, and by fitting a Gaussian function to the result.

Element	K_p [km s ⁻¹]	Center [km s ⁻¹]	SN@ $K_{p,\text{theoretical}}$
Na I	166 ± 39	-3.4 ± 0.7	3.0 ± 0.6
Fe II	164 ± 28	-4.0 ± 0.8	2.1 ± 0.6
Mg I	151 ± 0.031	-3.9 ± 1.3	2.9 ± 0.7

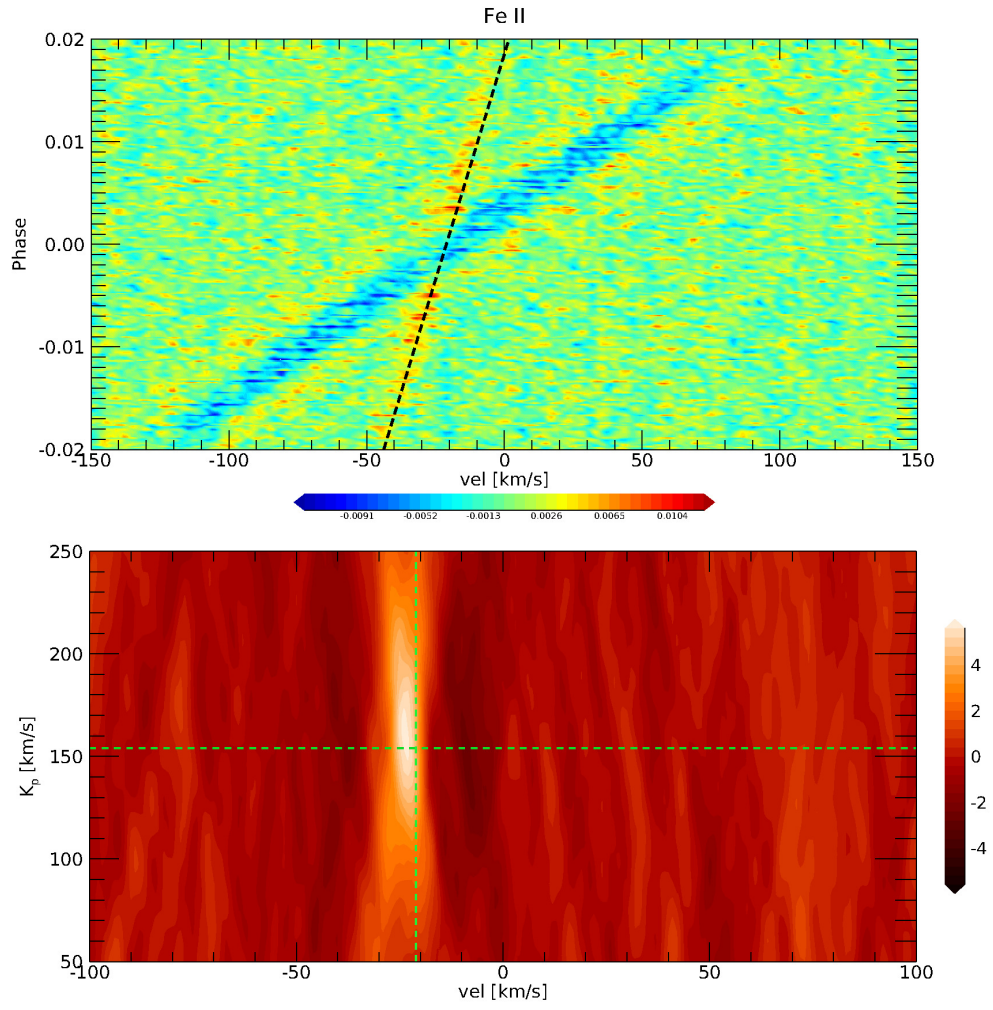


Fig. 7.16: Same as Fig. 7.15 but for Fe II

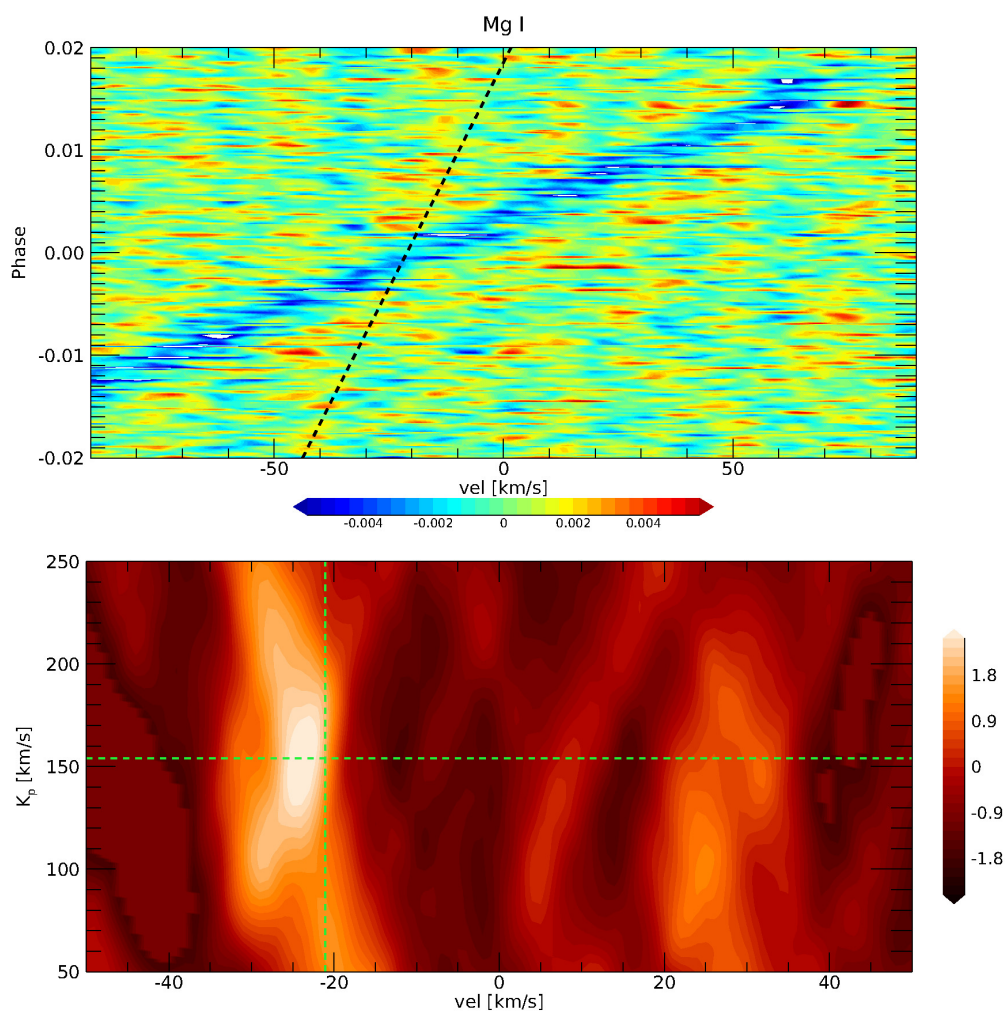


Fig. 7.17: Same as Fig. 7.15 but for Mg I

this shift is robust across independent studies and slightly different for each element it could be interpreted as a day-to-night side wind.

7.6.3.1. Cross-correlation with FeI models

Nugroho et al. (2020) found a double-peak shape in the $K_p - V$ maps of Fe I. The peaks have similar K_p , and they are roughly $\approx 10 \text{ km s}^{-1}$ apart, with the secondary blue-shifted peak weaker than the primary one. They reconstructed the observed structure by simulating two Fe I signals with different amplitudes and ΔV , and found the best match when masking the weaker signal (at $\Delta V = -10 \text{ km s}^{-1}$) from phase -0.01 and -0.016, simulating a delay in its appearance. My results are shown in Fig. 7.18: I found the double-peak feature quite clearly in the first two transits (2017-08-16, and 2018-07-12), while only the weaker blue-shifted signal is present in the third transit (2018-07-19). These are the same data analyzed by Nugroho et al. (2020). In the fourth and fifth transits (2019-08-26, and 2019-09-02) only the stronger signal is visible. The parameters show a clear variability, as reported

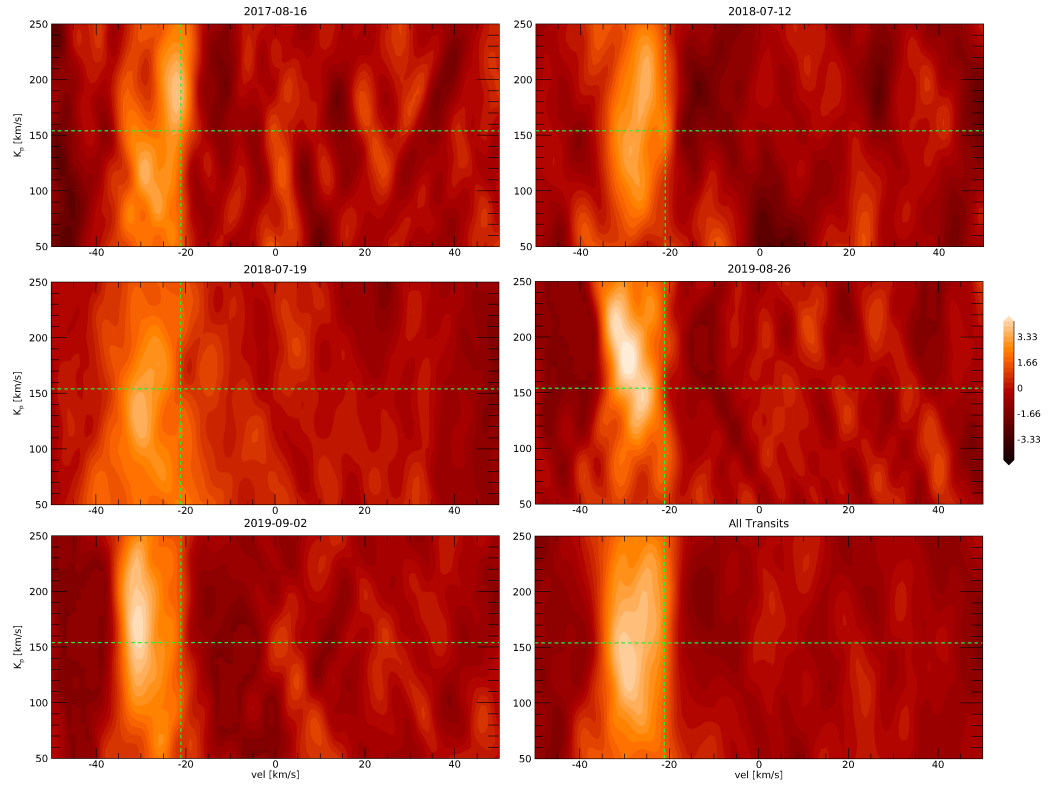


Fig. 7.18.: The K_p vs velocity map for the five transit nights and the combined data after summing the cross-correlations for different K_p . The colorbar scale is in S/N. Green dashed lines are centered on the expected planetary position.

in Table 7.5. With 5 transits showing the same overall pattern, I can confirm

Tab. 7.5.: Summary of cross-correlation detections in the atmosphere of KELT-20 b. Center and S/N are estimated for uniformity at the theoretical K_p value. The significance of the detections was calculated by dividing the best K_p cross-correlation function for the noise, and by fitting a Gaussian function to the result.

Night	K_p [km s^{-1}]	Center [km s^{-1}]	$\text{SN}@K_{p,\text{theoretical}}$
2017-08-16	186 ± 46	-1.3 ± 0.3	2.2 ± 0.6
2018-07-12	202 ± 56	-4.0 ± 1.1	2.1 ± 0.5
2018-07-19	131 ± 36	-8.9 ± 2.4	1.8 ± 0.7
2019-08-26	180 ± 35	-8.2 ± 1.5	2.5 ± 0.6
2019-09-02	167 ± 39	-10.0 ± 2.3	2.6 ± 0.4
All Transits	126 ± 31	-8.1 ± 1.9	2.4 ± 0.5

the presence of atmospheric dynamics with a progressive blueshift of the signal. A possible interpretation for the variations might be the variable contribution of different elements to the overall atmospheric signal during the transit: because the stellar mask contains different elements, all of them contribute to the resulting atmospheric trace, but their relative abundances may change during the transit due to, for example, temperature variations that may cause some of them to condense. The condensation of iron (Ehrenreich et al., 2020) may also play a role in this situation. The tool I created presents still some issue. As an example it is not able to mask the stellar signal that probably mitigates part of the signal from the planet. Moreover, using the whole spectrum for the cross-correlation might spread the noise during the iterations and this could be a cause for an additional dampening effect on the planetary signal. Nevertheless, I did find a very strong variability of the signal from one transit to another and I am able to retrieve a signal from the atmosphere of a planet using cross-correlation and I will be able in the future to enhance this tool in order to make surveys of exoplanetary atmospheres and search for elements.

7.7 Conclusions

The search for atmospheric signatures at high spectral resolution in the transmission spectra, obtained through the best spectrographs currently available is one of the main objectives of exoplanetary science. The information contained in those signatures are unique and are accessible just using a few instruments. In this sense, being member of the GAPS Atmosphere group was of crucial importance in order to have the possibility to work on top level data.

In particular, I created different tools that will help me to focus my research on weak signals. The first tool allows me to co-add the spectral lines of one single element in

the velocity space, enhancing the signal to noise ratio of the signal. Weak signals can thus be retrieved in an easier way, guiding the analysis of more detailed method such as cross-correlation. The second method I developed uses the cross-correlation of the transmission spectra with theoretical masks.

These tools allowed me to retrieve the signals of different elements present in the atmosphere of two ultra-hot Jupiters, KELT-9 b and KELT-20 b. I focused on the study of Mg I triplet, an important element that helps to describe the processes of atmospheric escape in hot Jupiters and that just recently was detected. I presented the results of my work on KELT-9 b Mg I triplet with a poster at “2019 Sagan Exoplanet Summer Workshop: Astrobiology for Astronomers”, a workshop that took place in Pasadena, during the period July 15-19, 2019. The cross-correlation method I developed was instead used to study the Fe I lines in the atmosphere of KELT-20 b for a paper submitted to a peer-reviewed journal (Rainer, ..., Frustagli et al., 2021).

Limitations of Exoplanet Atmosphere Studies at High Resolution

The study of atmospheric signatures at high spectral resolution in the transmission spectra obtained from the best spectrographs is currently one of our main goals. The information contained in those signatures is unique and it is accessible just through a few instruments and at certain resolutions. Therefore, understanding how to separate the signal due to the planetary atmosphere from other effects measured by the spectrographs is of crucial importance. In order to detect the exoplanet atmosphere's traces in the transmission spectra, we use differential techniques. Then we are also sensitive to all the variations that can appear in the form of spectral lines in times that characterize the transit. The spectral lines can be subject of temporal and/or spatial variations through different mechanisms on their contrast, their width (FWHM), their position (velocity) or their symmetries. Therefore, the passage of an exoplanet in front of different regions of the stellar surface will leave different traces in the transmission spectra. Among the effects that can modify the shape of an atmospheric signal or that can create “false signals” a non exhaustive list comprehends:

- The stellar rotation through the lines broadening and through the Rossiter-McLaughlin effect;
- The center-to-limb variation of the stellar lines;
- The stellar activity through the presence of active regions in the photosphere and in the chromosphere;
- Effects due to Earth's atmosphere behaviour, triggered by natural phenomena or artificial activities in proximity of the observing facilities.

Some of these effects can be corrected or at least separated from the atmospheric signatures. During my PhD I focused on Earth's atmosphere behaviour in the site of La Palma, in the attempt to find possible variations of the spectral lines of an element in Earth's atmosphere. Indeed, when dealing with small signals such

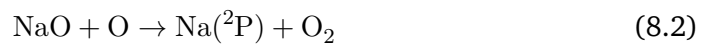
as those coming from an exoplanet, it is mandatory to avoid the influence of any external feature.

8.1 The Sodium D Doublet - the Airglow Issue

The early theoretical studies about exoplanet atmospheres stated that very strong planet spectral features are expected in transmission spectroscopy. Seager and Sasselov (2000) was one of the first works that predicted the presence of alkali metals lines as strong signatures. Indeed, assuming hot Jupiters' atmospheres are similar to brown dwarfs and cool L dwarfs which have similar T_{eff} values, the authors pointed out that their composition should be analogous too.

Charbonneau et al. (2002) verified these assumptions and discovered the first signatures of Na I absorption in the transmission spectrum at low resolution, using STIS onboard of Hubble Space Telescope. The measured Na I absorption in the atmosphere of the hot Jupiter HD 209458 b was $(23.2 \pm 5.7) \times 10^5$ deeper than in adjacent bands during transit, and weaker than model predictions by a factor of ~ 3 . Redfield et al. (2008) reported the first ground-based detection of an extrasolar planet atmosphere, a Na I absorption in HD 189733b of $(67.2 \pm 20.7) \times 10^5$ in the same band as Charbonneau et al. (2002). More recently, new studies (e.g., Wyttenbach et al., 2015; Seidel et al., 2020) showed that sodium can be not only detected, but also characterized exploiting the high-resolution of spectrographs.

Since sodium is one of the most studied elements in exoplanet atmospheres, it is worth noting that in the region of the spectrum that comprises the wavelengths of the sodium D doublet, Earth's atmosphere behaviour could contaminate the transmission spectra as telluric water and sodium overlie exactly in the same region. In the mesospheric sodium layer, that typically extends from 80 to 110 km in altitude and peaks in concentration at around 90 km, several processes can indeed activate sodium emission in the airglow spectrum. This phenomenon was first reported by Slipher (1929) and 10 years later recognized as due to the transition $\text{Na}(3^2P_J - 3^2S_{1/2})$ (Bernard, 1938). It is well-known that resonant fluorescence and photochemical excitations play a dominant role for the production and temporal evolution of Na airglow. The chemical scheme responsible for excitations of neutral Na atoms is as follows (Chapman, 1939)





The role of the Chapman chemical scheme in producing the Na airglow has been recognized over the years, even if there is widespread debate on the rate of these reactions and on the ratio of D_2 and D_1 , hereafter R_D , lines intensity. The emission intensity of the sodium nightglow is seasonal, with recent studies that show a strong semiannual oscillation (SAO), with peaks at the equinoxes and troughs at the solstices. About 85,000 people live in La Palma, mainly concentrated in 8 towns within 15 Km of the Observatorio del Roque de los Muchachos. Moreover, given the altitude of the site, the line-of-sight over the sea has a radius of ~ 180 Km, enough to intercept the lighting of Tenerife, the major of the Canary islands (800,000 inhabitants and 120 Km distant) whose coast is visible to the naked eyes on very clear nights. Despite the Canary Sky Law, introduced in 1992, limiting the type of outdoor lighting sodium lamps power and orientation with respect to the ground, there is still a possibility that light pollution can have an impact on the Na airglow and as a consequence on Na detection in exoplanet atmospheres. At high airmass, light from outside the atmosphere may be dimmed by scattering and absorption, but the airglow will probably be brighter, since a line-of-sight intercepts a larger number of atoms in the sodium mesospheric layer. For airglow arising in a thin layer at height h , the intensity should vary with zenith distance Z_D as

$$I_{Z_D} = \frac{I_0}{\sqrt{1 - \left(\frac{R_\oplus}{(R_\oplus + h)^2 \cdot \sin^2 Z_D} \right)}} \quad (8.5)$$

where $R_\oplus$ is the radius of the Earth. If a fraction f of the sky brightness is due to airglow, one expects the sky to be

$$\Delta Z_D = 2.5 \log_{10} \left(\frac{f \cdot I_{Z_D} + (1 - f) \cdot I_0}{I_0} \right) \quad (8.6)$$

mag brighter at zenith distance Z_D compared with zenith.

8.2 Measurements from La Palma

La Palma in the Canary Islands hosts Europe's largest Northern-hemisphere observatory, the Observatorio del Roque de los Muchachos. The observatory lies close to the island's peak, on the rim of a large volcanic caldera, at longitude 18°W , latitude 29°N , altitude 2300 m, geomagnetic latitude $\sim 20^\circ\text{N}$. Approximately 70%

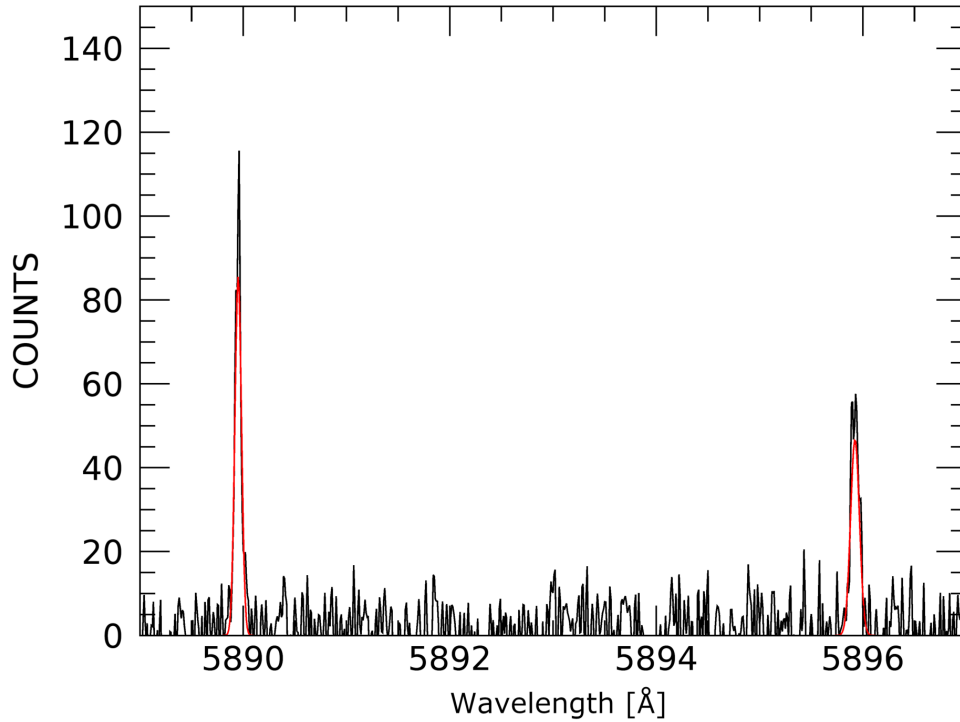


Fig. 8.1: HARPS-N sodium spectra, 5889-5997 Å.

of the nights are clear (95% in the summer) and 60% are photometric. The median site seeing is ~ 0.7 arcsec. The work to be described has made use of sky spectra generated from the 3.58-m telescope at the Telescopio Nazionale Galileo (TNG). TNG is coupled to the HARPS-N fiber fed, cross-disperser échelle spectrograph. One fiber is pointed on the object, the other one on a reference that can be either a Th-Ar lamp or the sky. I collected 4,769 spectra of the sky background from the archive of the TNG and analyzed them, in order to study possible variations of the sky emission. The spectra cover a wide range of samplings, from long exposures (1,800 sec) to shorter ones (900 sec). Dealing with different exposure times, I had to define a rescaling factor in order to have homogeneous results. Therefore, I normalized all the spectra by dividing them by the highest exposure time in the sample. In Figure 8.1 are shown typical sodium D_2 (5890 Å) and D_1 (5896 Å) line spectra from the TNG 3.8-m telescope in La Palma, using the HARPS-N échelle system. When dealing with a spectrum is necessary to understand what part of the signal is due to the signal from the source and what part is due to some sort of noise. For this reason, before analyzing the spectra I had to put some constraints on my data, in order to exclude spectra in which the sky sodium doublet emission

was too weak to be detected in the instrumental noise or to exclude processes not due to night sky emission.

First, I kept just the spectra in which the intensity of the sodium doublet lines was stronger than a noise threshold, defined as twice the mean noise of the spectra. In this way, the number of spectra significantly decreased from 4,769 to 2,980. Moreover, the data extracted from the sky fiber during twilight could be affected by the effects caused by the rays of the Sun. Therefore, I excluded all the data for which the solar elevation angle¹ was above the threshold of -18° . The final number of spectra I analyzed decreased then to 2,668. In the next Sections, the analysis of the variation of Na doublet intensity with airmass, time, and telescope's pointing direction is presented. The aim is to understand whether there are seasonal variations of sodium telluric emission and whether in the site of La Palma there is a privileged direction when pointing the telescope.

8.3 Variation with Airmass

Sodium lines intensity is plotted against airmass in Fig. 8.2. The relation between the the sum of the intensity of the sodium doublet lines is linear and it shows that the intensity emission is slightly stronger at airmass ~ 1.6 than it is at the zenith.

8.4 Variation with Time

As many previous measurements have reported, the Na layer exhibits seasonal variations: the total Na column density decreases to a minimum near the summer solstice and reaches a maximum in early winter. During mid-summer and the whole winter period, the Na abundance exhibits relatively small fluctuations compared with the much greater variability during the spring and autumn equinoxes. Figure 8.3 shows the Na lines intensity ratio plotted against date. The spread does not seem statistical, but it appears that there are minima and maxima in the overall distribution: the ratios are higher near the equinoxes, and there is an indication of a summer dip.

¹The solar elevation angle $\alpha_\odot$ is the angle between the horizon and the centre of the Sun's disc and it is complementary to the solar zenith angle $\theta_\odot$. They can both be calculated with the same formula, using results from spherical trigonometry,

$$\cos \theta_\odot = \sin \Phi \cdot \sin \delta + \cos \Phi \cdot \cos \delta \cdot \cos h \quad (8.7)$$

where h is the hour angle in the local solar time, δ is the current declination of the Sun, and Φ is the local latitude.

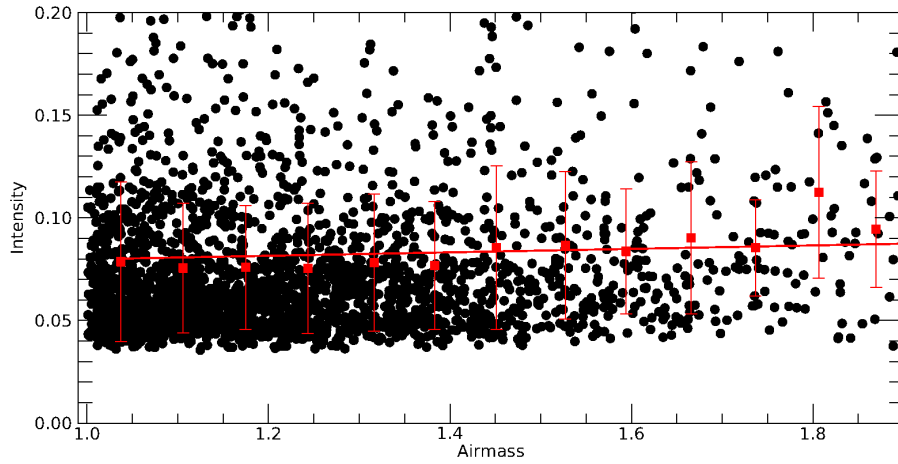


Fig. 8.2.: Sodium lines intensity plotted against airmass. Note, that the D_1 and D_2 Na lines are summed in order to have a higher signal-to-noise.

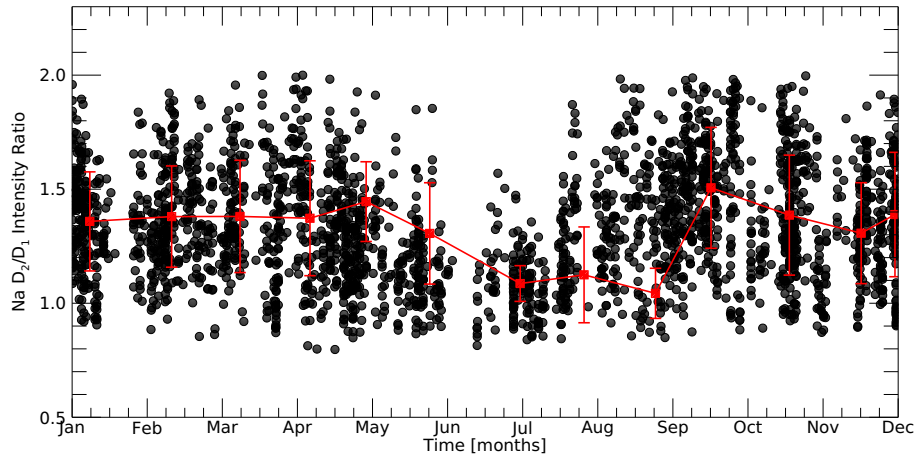


Fig. 8.3.: Seasonal dependence of sodium D_2/D_1 intensity ratios from HARPS-N data.

8.5 Variation with Pointing Direction

There is a direct line of sight from the observatory to sea level on the cities of La Palma island and the neighbouring islands of La Gomera, El Hierro and Tenerife. Clouds lying below the observatory often blot out streetlighting, although during the summer months they tend to be dispersed by warm winds. Azimuths (north through east), populations and distances of potential light-polluting communities are summarised in Table 8.1.

Place	Azimuth [deg]	Population	Distance [km]
Barlovento	50	2,400	10
Los Sauces / San Andres	110	5,700	12
Tenerife	115	908,000	130
Santa Cruz	125	16,500	15
Brena Alta/Baja	140	11,000	15
La Gomera	140	25,000	90
El Paso	180	7,500	12
El Hierro	190	10,100	110
Los Llanos / Tazacorte	200	25,00	12

Tab. 8.1.: Possible sources of light pollution at the observatory on La Palma.

Figure 8.4 shows the distribution of the spectra in the different regions of the sky. The points are equally distributed in all the directions, meaning that my sample covers the whole sky. Note that there are only a few data below 30 °of latitude. Therefore, in the following analysis, I excluded the spectra below this threshold in order to avoid that the interpolation of these few data when plotting the coloured map could lead to a wrong interpretation of the results. The two panels of Fig. 8.5

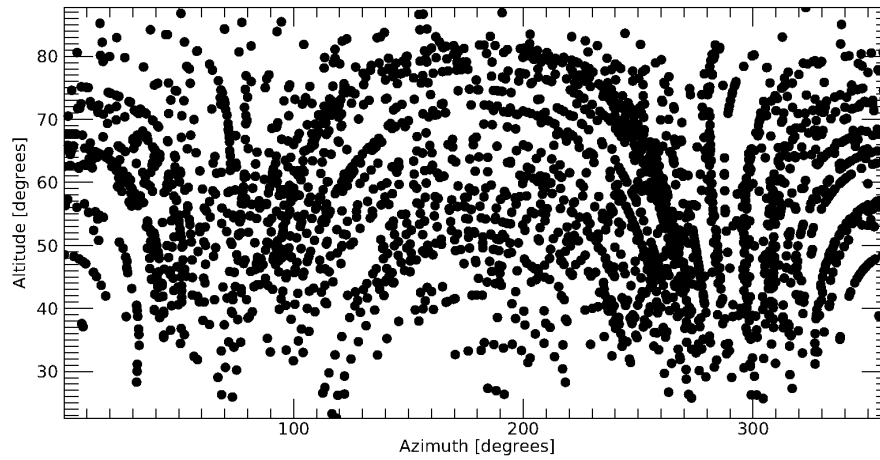


Fig. 8.4.: Sky distribution of the 2,668 HARPS-N spectra. The data sample is equally distributed, however there are only a few data below 30° of latitude.

show the coloured maps of the sky using the intensity of the two lines of Na doublet as third parameter. The red spots point out where the intensity of the emission is stronger and they are equally distributed in the map, therefore it is possible to infer that there is not a clear privileged direction for Na emission. In the top and bottom

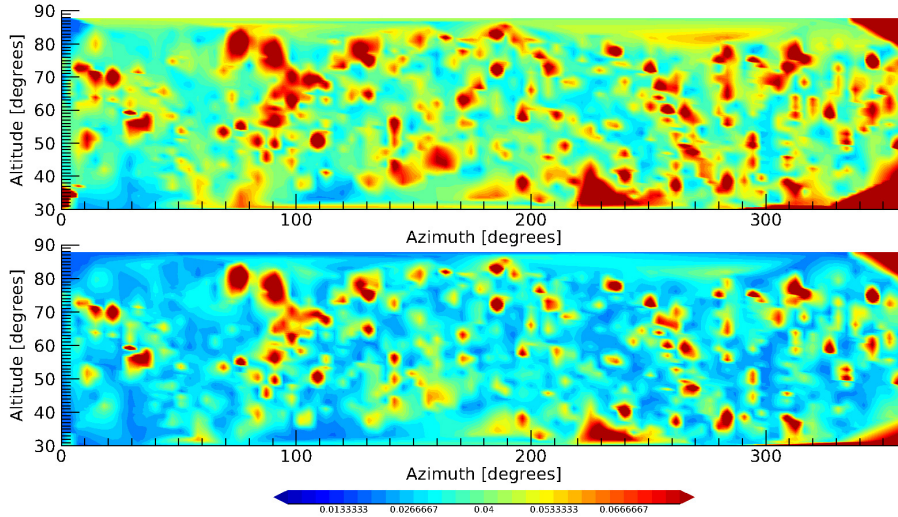


Fig. 8.5.: Sky maps of the intensity of the two lines of Na doublet. *Top panel:* Intensity of the Na D₂ line emission in the sky around TNG. *Bottom panel:* Intensity of the Na D₁ line emission in the sky around TNG.

right corners of the maps, there are two clear red spots, but they are most probably due to the few spectra available in that part of the sky. There is another clear red spot between 220° and 240° of the azimuth coordinate. The interpretation of that spot is harder since, as pointed out in Table 8.1, there are no cities in that direction. Yet, the emission seems to be stronger in that spot than in other zones of the map and this could be due to some mechanisms happening in that part of the sky or again to a lack of sky spectra available in the sample, or to a combination of the two options.

Finally, the four panels of Fig. 8.6 show the coloured map of the sky surrounding the TNG in four different periods of the year. Top panel shows the Na emission lines intensity in spring, and exhibits some clear red spots due to emission at high altitude (60° to 90°). The second panel presents the intensity of the lines in summer, in this case the emission spots are less evident, probably underlining the results from the previous Section in which it was clear the reduction of emission during this period. In the third panel, the intensity of Na lines in autumn is shown. The emission red spots in this panel seem to be more uniform and well distributed along the whole line of sight around the TNG. Particularly interesting are the emission in the high atmosphere (90°) and in the latitudes between 100° and 200°, where most of the cities are condensed. The fourth panel shows the behaviour of the sodium lines in winter. The intensity of the lines decreases again and the emission spots are randomly distributed in the sky. The emission at low altitude is still strong between 100° and 200°, but weaker than in autumn.

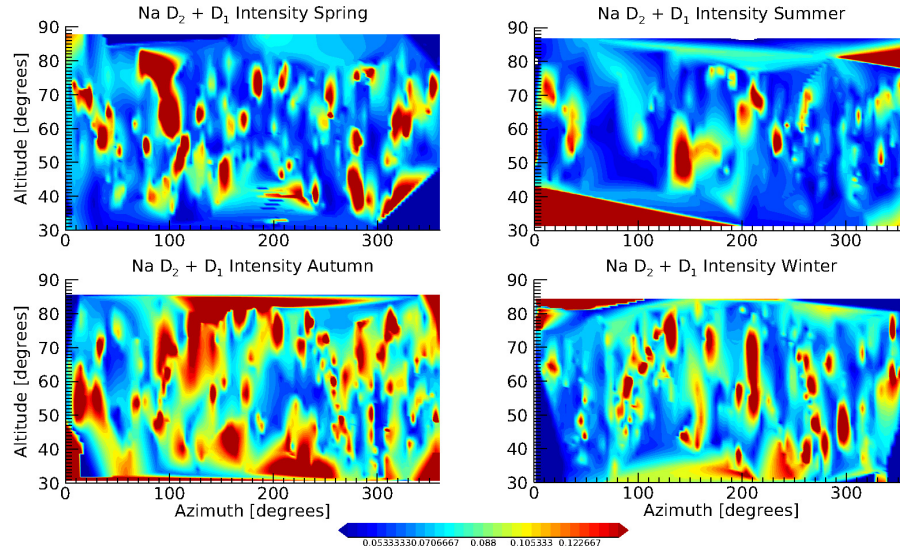


Fig. 8.6.: Sky maps of the intensity of the two lines of Na doublet. *Top left panel: Top right panel: Bottom left panel: Bottom right panel:*

8.6 Discussion

The variability of the Na D-lines in the night glow is a phenomenon that could have some influence on exoplanet atmospheres characterization and needs to be investigated in order to find possible explanations and solutions. During my first year of PhD, I downloaded more than 4,000 sky spectra from the TNG archive and analyzed them in order to find possible relations between the intensity of the sodium doublet lines and three different factors: airmass, time, and the telescope's pointing direction.

The number of spectra that I kept for the analysis do not allow me to draw firm conclusions about the results, however it is possible to point out a few facts. First, my analysis shows that there is not a clear evidence of strong variations with airmass. Second, no privileged direction when pointing the telescope emerges, but the distribution of emission is homogeneous in the sky. Third, from the analysis of the Na doublet ratio intensity against time, there is an evidence that the emission has a minimum in summer and maximum in autumn.

The observed variation of Na intensity ratio exhibiting increase, decrease and periodic fluctuations shows the dynamic behaviour of the atmosphere. What are the causes of this behaviour? The answer to this question goes beyond the purposes of this analysis, since a deeper comprehension of Earth's atmospheric processes is necessary, but still a number of possible explanations will be explored. The seasonal variation observed in the data suggests that temperature might play a role and the Chapman

chemical reactions could be temperature dependent, but previous studies (e.g., Slanger et al., 2005) tend to exclude this possibility, pointing out that the intensity ratio is not temperature dependent over the temperature range appropriate to the upper mesosphere. Another possibility is that the sodium emission is produced by a completely different chemistry that competes with the Chapman mechanism. The only gas-phase chemical reactions that are sufficiently exothermic to produce Na(²P) in the upper atmosphere are dissociative electron recombination reactions of Na⁺ cluster ions, but the problem with this possibility is that the rate of cluster ion formation is too slow for this mechanism to compete significantly with the Chapman mechanism (Cox and Plane, 1998). A third possibility could be the input in the mesosphere of major sodium species Na, Na⁺, and NaHCO₃, through, for example, meteoric ablation, and eventual removal of these species from the gas phase via condensation onto particles. The problem with this prospect is that the rate of meteoroid input in the atmosphere could be too low to cause a significant increase of the nightglow. Finally, as I already pointed out, another possible cause of the sodium nightglow is light pollution given by artificial illumination. However, given the few spectra taken at low altitude, it is difficult to understand the impact that this phenomenon has on sodium emission.

My analysis of sodium emission underlined that Na D-lines emission slightly changes during the year. The results are not conclusive, as the sample of spectra I was able to keep for my analysis is very reduced with respect to the initial one. A more focused analysis of the sky spectra could help us to understand if sodium emission has an impact when we analyze the transmission spectrum of an exoplanet. A detailed analysis could also take into consideration other elements observed in exoplanetary atmosphere and the influence that Earth's atmosphere has on our observations. This type of analysis would be of extreme importance not only for the observations from the TNG observatory, but also on other important sites. I believe that it could help us to prepare the sites for the next generation telescopes, whose instruments will be so sensitive that also slight variations generated from our atmosphere could make the difference between the detection or the non-detection of an element line in an exoplanet atmosphere.

Part III

PhD Experiences and Conclusion

Conclusions

” It has been said that astronomy is a humbling and character-building experience. There is perhaps no better demonstration of the folly of human conceits than this distant image of our tiny world. To me, it underscores our responsibility to deal more kindly with one another, and to preserve and cherish the pale blue dot, the only home we’ve ever known.

— Carl Sagan
(Pale Blue Dot: A Vision of the Human Future
in Space)

My thesis, done at INAF - Osservatorio Astronomico di Brera in Merate, has focused on different aspects regarding the characterization of exoplanets and their atmospheres. I had the opportunity to work with different groups and confront my opinion with many researchers from all over the world, developing my own ideas about the different topics I addressed.

In the frame of the GAPS (Global Architecture of Planetary Systems) project, a collaboration of mostly Italian experts in the field of exoplanets, I was able to work on the two main projects in which it is involved: radial velocity analysis of young objects and the atmospheric characterization of exoplanets using data from the ultra-precise and stable spectrograph HARPS-N installed at the TNG.

For what concerns the GAPS Young Objects program, my study of radial velocities was centered on the target TYC 4610-1318-1, that we called YO-09. This star was monitored in two different campaigns, for a total of 38 high resolution spectra collected. I performed a frequency analysis of the RV and of the main activity indicators time series. I also used the python routine PyORBIT in the attempt to find a possible planetary signal hidden in the RV time series. My analyses resulted in a null detection of significant signals, with the conclusion that there is no strong evidence for a model with at least one planet, even though a planet in this system

cannot be completely excluded. However, working with other people from the group, I was able to learn from them, to share the knowledge, and to compare the results.

My work with the GAPS Atmosphere program was a larger part of my involvement in the GAPS project. First, I focused on Earth's atmosphere and in particular on the sodium emission in the sky around TNG. I studied more than 4,000 high resolution sky spectra from the TNG archive and analyzed them. The goal was to study possible variations of the sky emission with time, airmass and telescope's pointing direction. My analysis shows that there is not a clear evidence of strong variations with airmass. Also, no privileged direction when pointing the telescope emerges, but the distribution of emission is homogeneous in the sky. Furthermore, from the analysis of the Na doublet ratio intensity against time, there is an evidence that the emission has a minimum in summer and maximum in autumn.

Unfortunately the careful selection I operated on the sky spectra, reduced significantly the number of data that I kept for the analysis and this did not allow me to draw firm conclusions. Nevertheless, I was able to obtain some interesting results that could be useful for more detailed analyses in the future and made me understand some of the challenges we have to deal when we analyze the spectra we observe.

Second, I developed my own tools for the analysis of exoplanets atmospheres in transmission. In particular, I used the spectral data of two inflated ultra-hot Jupiters, KELT-9 b and KELT-20 b, and addressed my studies on weak metallic lines such as the magnesium triplet. The first method I developed follows previous approaches for high-resolution spectroscopy but allows me to co-add the spectral lines of an element in the velocity reference frame, enhancing the signal-to-noise ratio and being able to tell whether the element is present in the exoplanet's atmosphere. I detected significant absorption in the transmission spectrum for Na, H, Fe and Mg I, and I certified their planetary nature by using the 2D tomographic technique.

The second tool cross-correlates the transmission spectrum of the planet with a template spectrum, focusing on the discernment of the presence of specific elements in the atmosphere. I analyzed the high-resolution spectra of KELT-20 b and with the cross-correlation technique I confirmed previous detections of Fe I, Fe II, Mg I, and Na I. In particular, the planetary atmospheric signal during transit shows an overall blueshift of $\approx 10 \text{ km s}^{-1}$. I also explored the possible variation in the structure and position of the Fe I signal in different transits.

Thanks to this work, I was able to expand my knowledge in a field that is rapidly growing up in the last few years, to compare my results with those present in literature, to understand what elements can currently be considered for observations, and what improvements the next generation instruments will bring.

I also became a member of the HARPS-N GTO Collaboration and had the opportunity to guide the analysis of an object that belongs to the ultra-short period planets, objects that orbit their stars with extremely short periods, smaller than about $2R_{\oplus}$ and compositions similar to that of the Earth.

Using the K2 data for the G2 star HD 80653, I studied the different aspects of the analysis of transits, including the detrending of the light curve and also considering the secondary eclipse. The planet discovered by K2 Campaign 16, HD 80653 b, is a super-Earth planet ($R = 1.608 \pm 0.071 R_{\oplus}$) transiting the star on a short period orbit ($P = 0.719573 \pm 0.000021$ d). I examined the radial velocities and the activity indicators of HD 80653 extracted from the HARPS-N high resolution spectra and characterized the planet.

From our radial velocity measurements, we constrained the mass of HD 80653 b to $M = 5.60 \pm 0.43 M_{\oplus}$ and derived the bulk density ($\rho = 7.5 \pm 1.1 \text{ g cm}^3$) of the planet, consistent with an Earth-like rocky/iron composition and no thick atmosphere. The results have been summarized in a paper submitted to a peer-review journal (Frustagli et al., 2020).

The long term trend I found in the RV data pushed us to continue the RV monitoring of the system, extending the time baseline, and we were able to tighten the constraints on the orbital parameters and mass of a long period companion of the USP super-Earth. The observations are currently ongoing, but the new data suggest that the companion has a period of $P_c = 956.39^{+20.80}_{-19.62}$ d, with a high eccentricity $e = 0.836 \pm 0.011$, and a mass limit of $M_c \sin i_c = 5.16^{+0.24}_{-0.22} M_J$. The analysis will be refined and the results will be reported in a paper (Frustagli et al., in prep.).

9.1 Schools

During my PhD, I had the opportunity to attend to some Schools and Workshops, that gave me the opportunity to improve my knowledge of exoplanets and exoplanetary science, learning from experts in different scientific fields.

9.1.1 Third Advanced School on Exoplanetary Science

The “3rd Advanced School on Exoplanetary Science” took place in Vietri sul Mare in the period May 27-31, 2019. In this school I learned why the demographics of exoplanets is so important in order to discern and understand the underlying populations and planets that produce the observed distributions we see. I gained a clearer view of the current limitations on our ability to discern the true underlying

planet population from the observed distribution, a deeper comprehension of what the size and/or mass distribution of exoplanets can teach us about the dominant planet formation, migration, and evolution pathways, and a better understanding of the stellar properties that affect the types of planets that form, and how can we use these properties to study planet formation. This experience was very important to give me a boost in my knowledge of exoplanetary science, in particular on the importance of deeply understand how to relate observations with theory, how many physical phenomena must be taken into account when dealing with the statistical study of exoplanets populations. Moreover, this school gave me the chance to relate with young researchers from many different countries as well as meet top researchers in the field, talk to them, and discuss of the topics that interested me the most.

9.1.1.1. Planet formation

Professor Alessandro Morbidelli, from the Observatoire Cote d'Azur, gave us an exhaustive overview of planet formation and in particular the detailed description of six key mechanisms:

- The structure and evolution of protoplanetary disks, with the main models now considered (viscous-disk model and the wind-dominated model);
- The formation of planetesimals, macroscopic bodies formed by the collision of grains of dust inside the protoplanetary disks;
- The accretion of protoplanets and the ways in which the planetary embryo grows and forms a planet: runaway growth, oligarchic growth, and the pebble accretion model;
- The small planets migration under that process called Type-I migration, its dependence of the disk characteristics, and the current knowledge theoretical and observational limitation;
- Giant planets formation, gas accretion and Type-II migration and the accordance between models and observations;
- Resonance trapping, that is the tendency of multiple planets to lock into mutual mean motion resonance, and the reasons why we find resonant planets in some case and not in other.

9.1.1.2. Dynamical evolution

The second lecturer, professor Sean Raymond (Laboratoire d'Astrophysique de Bordeaux) showed us the observational constraints and the key processes related to the dynamical evolution of exoplanets. The connection between observations and theory is fundamental to understand how different combinations of processes drawn from a common set of physical mechanisms can explain the diversity of the planetary systems observed:

- Summary of the main observational constraints from protoplanetary disks for planet formation models (e.g., disk lifetime, disk masses, disk structure) and from extrasolar planets (e.g., demographics, occurrence, orbital distribution);
- Close-in super-Earths main formation models (in-situ accretion and the migration models) and how they match the key properties of super-Earth systems we observed to date;
- The essential observational constraints on giant planets formation and dynamics, and how they lead to the two main models, the collapse scenario and the core-migration-accretion model;
- The classical model for the Solar System formation and how the simulations lead to the so-called 'small Mars' problem;
- The three main models that revolutionized the way we think to the Solar System formation: the Grand Tack model, the Low-mass Asteroid belt model, and the the Early Instability model;
- The six water delivery or water production mechanisms that originated water on Earth and how to extrapolate what we understood about them to rocky exoplanets.

9.1.1.3. Close-in Exoplanets

Andrew Howard, professor at the California Institute of Technology, presented us the characteristics of close-in exoplanets and their observational properties:

- Review of radial velocities and transit methods, the impressive results reached, their points of strength and their limitations;
- The mass, size, and period distribution with the goal to understand what are the major occurrence trends in RV and transit searches;

- The importance of the mass-radius diagram, the transition from super-Earths to sub-Neptunes, and what phenomena can influence the diversity of planet core masses and compositions;
- The characteristics of multi-planet systems and how we can use possible patterns we find in their demography to test planet formation theories;
- The dynamical temperature of exoplanetary systems and how we match the obliquities, inclinations, and eccentricities observed with models;
- The characteristics of systems that host ultra-short period planets.

9.1.1.4. Wide-separation Exoplanets

The fourth lecturer was professor Scott Gaudi from Ohio State University. In his lectures he focused his attention on exoplanets with wide orbits:

- Review of the characteristics and of the points of strength of the five main methods for exoplanets detection;
- The overlap of the different exoplanetary surveys, their sensitivities and how they can be used to better define the demographics of exoplanets;
- Lessons learned from microlensing and direct imaging surveys, the two best methods to detect distant planets;
- The difficulties of RV and transit surveys in the study of wide-separation planets and the constraints these methods can help to put on this type of exoplanets;
- How to synthesize the results from various methods and how to compare what we get to planet formation theories;
- The future of exoplanetary science and the missions that will bring forward our knowledge of exoplanets.

9.1.1.5. Star-Planet Interactions

Professor Antonino Lanza, from the Astrophysical Observatory of Catania, illustrated us the theory behind the interactions between stars and planet:

- How the planet interacts with the gravitational field (tidal forces);

- The tides play a relevant role in the orbital evolution and in the habitability of close-in planets;
- Stellar irradiation as a strong element influencing the exoplanet atmospheric dynamics, with a particular focus on evaporation;
- Interaction between the magnetic field of the star and the planet.

9.1.2 Second Astrostatistics School

The “2nd Italian Astrostatistics School” took place in Milan in the period June 24-28, 2019. The focus of this school was to train astronomers to the use of modern statistical techniques, specifically parameter estimation and model selection. The goal was pretty clear, giving to the students the recipes for a good statistical analysis.

9.1.2.1. Basic Theory

The school introduced me to the the basics of the probability theory needed for Bayesian statistics. First of all, I learned the three practical rules behind the concept of probability, Kolmogorov’s axioms:

1. Probabilities are bounded between 0 and 1. In formulae:

$$0 \leq p(E) \leq 1 \quad (9.1)$$

for some object E.

2. The probability that at least one of all the possible outcomes of a process will occur is 1. In formulae:

$$p(E) = 1 \quad (9.2)$$

This axioms ensures that the probability that we will observe the event is one. It immediately follows that

$$p(\emptyset) = 0 \quad (9.3)$$

where $\emptyset$ is the empty set, and this formula implies the probability of observing an empty set of events is zero.

3. This is the sum or marginalization axiom. It states that any countable sequence of mutually exclusive events E_1, E_2 , etc. satisfies

$$P\left(\bigcup_{i=1}^{\infty} E_i\right) = \sum_{n=1}^{\infty} P(E_i) \quad (9.4)$$

i.e., it affirms that if we have two mutually exclusive events, then the probability of either occurring is the probability of one occurring plus the probability of the other occurring.

Secondly, I learned the product rule, another fundamental instrument for statistical analysis. This rule states that the joint probability that two events E_1 and E_2 will occur is equal to the product of two terms, the probability that event E_2 occurs, and the probability that E_1 occurs given that E_2 has already occurred. In formulae:

$$P(E_1 \cap E_2) = P(E_1 | E_2) \times P(E_2) \quad (9.5)$$

It immediately follows that

$$P(E_2 \cap E_1) = P(E_2 | E_1) \times P(E_1) \quad (9.6)$$

From this formulae, it is possible to derive Bayes' Theorem, the most important rule for modern statistical analysis. As $P(E_1 \cap E_2)$ and $P(E_2 \cap E_1)$ are equal, rearranging Eq. 9.5 and Eq. 9.6, the general formulation of Bayes' theorem is

$$P(E_1 | E_2) = \frac{P(E_2 | E_1) \times P(E_1)}{P(E_2)} \quad (9.7)$$

The name of the events can be rearranged as follows, to adapt the Bayes theorem for the analysis of data:

$$P(\theta | data) = \frac{P(data | \theta) \times P(\theta)}{P(data)} \quad (9.8)$$

where the term θ is the observable event, $P(\theta | data)$ is the term that indicates posterior probability, $P(data | \theta)$ is the likelihood, $P(\theta)$ is the prior probability, and $P(data)$ is a normalizing constant.

9.1.2.2. From Theory to Practice

The theoretical basis learned in the first part of the school was immediately used in extended laboratory sessions in order to develop some experience by practicing with models of increasing difficulty.

The hands-on exercises proposed started with simple examples, a step-by-step guide for building a Bayesian model. The increasing difficulty of the exercises helped me to understand how a complex model is built and used in real scientific cases. I also understood how to check if the model adequately describes the data through simulations, and how to modify the fitted model until its adequacy is demonstrated.

9.1.2.3. What I took home

The school gave me a good introduction on Bayesian statistical approach and it will be a good starting point for enhancing my knowledge on this topic. I will definitely need more practice before being able to apply this type of analysis to my work, but I am confident it will give me the chance to obtain even more effective results for high quality science.

9.1.3 2019 Sagan Summer Workshop

The “2019 Sagan Exoplanet Summer Workshop: Astrobiology for Astronomers” took place in Pasadena, CA, during the period July 15-19, 2019. This workshop featured introductions on the formation of Earth and terrestrial planets, their evolution over time, current geochemical cycles on Earth, and the emergence of life on Earth. It increased my knowledge of Exo-Earths, including demographics, composition, atmospheric signatures, and comparison with Earth. Detection of biosignatures, with an emphasis on false positives and false negatives, have also been discussed, as well as the future instruments that will bring a great improvement in the field. This workshop gave me a complete overview of the state-of-art comprehension we have on origins, evolution, and detection methods of habitable planets and life outside Earth.

9.1.3.1. Formation and Evolution of the Earth and Other Solar System Bodies

The first day of the workshop was dedicated to planetary formation and evolution, and to the development of the atmosphere. Earth was taken as an example of habitable planets, and the talks focused on its formation and development through its history.

The invited speakers presented the modern theories of planetary formation, focusing on terrestrial type planets, since these planets are more likely to support conditions for habitability. I had the chance to learn what we know about Solar System

and rocky planets development, not only from an astrophysical point of view, but also geological and geochemical. I gained a good understanding on how Earth grew out from dust and became a planet with its own atmosphere, derived from complex geological processes and how this processes are tightly connected with the environment in which they set in.

9.1.3.2. Origin and Evolution of Life

The main topic of the second day was life on planets, its origin and its evolution mainly from a biological point of view. Once again, the example was Earth, since it is the only place we know life exists.

The speakers introduced the theories of life formation and evolution. Biochemistry and biology have been the subjects I had the chance to encounter during this day. The chemical elements important for life, the ingredients that help these elements to mix and form complex molecules, and the concept of biosphere and its contribution in the planet development are just some of the topics I had the opportunity to deal with.

9.1.3.3. Life on Other Planets

During the third day we started exploring the possibility of life presence on other planets. The speakers indicated possible pathways for detecting life in the Solar System and extend then our search to more distant planets.

The speakers pointed out on the fact that terrestrial biofluxes have enabled researchers to make progresses in this field, despite not having a reason to believe Earth's biofluxes to be universally applicable. Terracentricity of our models is inevitable, but the efforts to move beyond are an on-going work. In particular, two separated but related paths forward can be taken into consideration. One path is to continue to create models with biofluxes as free parameters and considering planets more and more different from Earth. The second path forward considers a wide range of molecules, not only those produced by life, but also all those that are both stable and volatile at a wide range of habitable atmospheric temperatures and pressures.

Whatever approach we use, we need to consider some caveats in order not to be fooled by our preconception, and keep an open mind.

9.1.3.4. Biosignatures

The fourth day was dedicated to biosignatures and the criteria they have to meet in order to enhance the probability that the biosignature can be detected and interpreted as being due to life: reliability, survivability, and detectability. An observed feature of the planetary environment can have a biological origin or it is more likely to be produced by life than by planetary processes and reliability is the criterion we use to discern its possible origin. The survivability criterion determines whether the candidate biosignature gas can avoid the sinks in a planetary environment and build up to detectable levels. Finally, the detectability criterion investigates whether the gas is spectrally active and clear of overlap with other chemical species in the wavelength region to be observed by techniques such as transmission, secondary eclipse, phase curves, and direct imaging.

These three criteria will help us to rule out possible false positive mechanisms and have a better understanding of the evolution of planets in the habitable zone.

9.1.3.5. The Future: Detecting Biosignatures on Exoplanets

The fifth and last day the topic treated the prospects for detecting exoplanets biosignatures. The future actual detectability of any biosignatures will be related to a variety of factors, including those related to the observing telescope architecture, target system distance and qualities, planetary parameters, and the accessible spectral range that will depend both on variables related to the telescope and target system.

The detection of exoplanet biosignatures is expected to follow a trajectory where interesting planet candidates are identified, for example, by the TESS mission, the PLATO 2.0 mission, or ground-based radial velocity or transit surveys. Intensive characterization will be then performed by the JWST mission, extremely large ground-based telescopes (ELTs; first light in mid-2020s), or a future direct-imaging mission such as the envisioned LUVOIR or HabEx missions (mid-2030s launch).

The detection of life across light year distances will be one of the most difficult measurements ever made, with a path full of hurdles and discoveries that we cannot predict yet. However, powerful instruments and careful inquiry should make it possible within the next few decades.

9.1.3.6. Lunches with Speakers and Hands-on Sessions

During my experience at Caltech I had the possibility to meet the dynamic American part of astrobiology and exoplanetary scientists, talk to them and exchange both opinions and ideas on this research field. The lunches with speakers have been an excellent opportunity to meet authors of the papers I read, to get a deeper comprehension of topics I got interested in, and understand how researchers in other fields approach the topics of habitability and the evolution of life in the universe.

During the 2019 Sagan Workshop there were hands on sessions. As a participant in the hands on sessions I worked into a small group to complete a project that we presented on the last day afternoon. We were provided with a set of simulated exoplanet reflection spectra containing both statistical noise and instrumental effects, such as might be obtained with a high-contrast coronagraph coupled to a large space telescope. Thanks to this work we had the opportunity to approach the data with an open mind, in order to attempt to classify the planets, and identify potentially habitable ones for follow-up observations. While doing this, we also investigated the data quality and instrumental requirements needed to properly identify habitable (or inhabited) exoplanets. This experience let me deal with very faint spectra, making me aware of the potential pitfalls when working and interpreting relatively low-quality data that can contain a wealth of information, in a situation where many basic parameters of the planets are unknown.

9.2 PhD Courses

During this three years I attended several courses organized at Università degli Studi di Milano Bicocca. I took part to both specific and interdisciplinary courses, having the chance to enhance my knowledge in topics related to astronomy and astrophysics, but also other skills, in particular those related to scientific communication.

9.2.1 PhD Specific Courses

The different specific courses were in some cases a good resume of what already learned during the Master's Degree at university, in others an interesting review of some fields of astronomy different from mine.

9.2.1.1. The Role of Baryonic Processes in Galaxy Formation and Evolution

This course took place on January 2018 and the lecturer was Professor Michele Fumagalli from University of Durham. The topics of the course were divided in two parts. The first part of the course covered the processes related to the interaction between matter and radiation, expanding my knowledge of the radiative transfer and dust extinction processes, the reactions in the interstellar medium and the heating and cooling mechanisms that occur in it.

The second part explored the processes related to baryons in galaxies. This gave me a better understanding of halo collapse and the hot/cold accretion, as well as the paths through which stars form. Professor Fumagalli also gave us a general introduction to the equilibrium model of galaxies and the importance of galactic winds.

Thanks to this course I acquired a general comprehension of these arguments, that will allow me to read and understand papers and talks related to the subject.

9.2.1.2. Gamma Ray Bursts: from Observations to Physical Models

I attended this course between May and June 2019. The lecturer was Professor Giancarlo Ghirlanda from INAF - Osservatorio Astronomico di Brera. He illustrated us the most recent developments in Gamma Ray Bursts (GRBs) field. We reviewed the observational properties of GRBs and how scientists interpret them, the different phases and emission mechanisms of GRBs, and the properties of relativistic jets. The course also explored GRBs as a counterpart of gravitational waves and as a tool to probe fundamental physics and cosmology.

The last part of the course was dedicated to the current and future instruments that will allow the GRBs' community to further investigate this field and enlighten the mechanisms behind these phenomena.

As a consequence, thanks to this course I had the occasion to go deeper into a different field of astrophysics, read papers related to it, and find connections with the field of exoplanets.

9.2.2 PhD Interdisciplinary Courses

9.2.2.1. Writing of Scientific Papers

I attended the course, lectured by professor Vanoni, in 2018. The lectures aimed to give us the basic skills necessary to design, structure, organize and write a scientific paper to be submitted to peer reviewed international journals.

The course focused on different points, starting from how to read a scientific paper and recognize its purposes, give an objective comment, and argument what could have been done differently in the analysis.

For what concerns the composition of a paper, we adopted the “write first-do-the-experiments-later” approach, as it is one of the bests in order to write a document good for publication. It is a method that allows us to stay focused and to be clear. This is helpful to crystallise what we do not fully understand and opens the way to dialogue with others through reality check, critique, and collaboration.

In order to learn the way a good scientific paper has to be written, we studied and analysed the different parts that compose it. Every part of a well written scientific text must contribute to communicate the idea we had and how we want to put this idea in a wider context, comparing it to other people’s approaches. Hands-on and practical exercises had a great importance in this process. We divided the structure of a paper in several sections and tried to recognize a common pattern and the characteristics every section must have.

Professor Vanoni highlighted also the importance of using a simple, direct language and a straightforward style. In conclusion, this course gave me excellent tools I will be able to use when I write a paper, but I will need to sharpen these tools with experience.

9.2.2.2. Scientific Communication in Theory and in Practice

This course, lectured by professor Andrea Cerroni, took place in 2018. The aim was to develop our sensitivity and ability about the most relevant issues both in the productive system of contemporary science and in scientific communication.

The lessons were organized as an active discussion, starting from common opinions about science with the goal to arrive to build a vademecum of what the goals of science communication are today.

The course introduced the study of science as a social production. After the presentation of fundamental sociological concepts such as individuals, institutions, knowledge,

and communication we discussed the naive model of scientific discovery, arguing how society enters into observations, categorizations, formulations of hypotheses and in their controls. Therefore, we examined the process of institutionalization of knowledge and addressed the diffusion of knowledge, distinguishing between information, popularization, and knowledge communication.

Professor Cerroni also introduced the fundamental concepts of the communication of science and innovation. After presenting the deficit model, we went deep into the mid-twentieth century shift in the public perception of innovation, distinguishing uncertainty, danger, risk and outrage. Therefore, he presented the phenomenology of daily risk, the levers of trust for delegation (competence, accountability, responsibility, participation), and the subjective estimation in choices in risky conditions. Finally, the lectures introduced us the communication modalities of public engagement in science and technology and the most recent participatory perspectives, the so-called citizen science.

Concluding, this experience taught me what are the principles and the abilities needed to communicate in science today. Effective communication is something that a good researcher needs to learn how to do it, in order to provide an invaluable service both to the scientific community and to the public building bridges between divergent cultures. The goal is not to become a professional communicator, but rather to infuse our culture with principles that successful communicators use to reach nontechnical audiences.

9.3 My PhD Experience

During the three years of PhD, I had great opportunities to develop my skills and expand my knowledge in the field of exoplanetary science. I got to know that a great part of the worldwide exoplanet community and discovered it is a very helpful and encouraging environment. Every time I wrote to authors of papers asking for enlightenment about things I did not understand, I received satisfying answers and useful advises for my work. In this sense, the GAPS and GTO experiences taught me the advantages and the difficulties of working in projects that involve many people. We shared information and expertise and I found it was a really useful way to increase my scientific knowledge and our ability to solve scientific problems. I really appreciated this, because the idea that, despite the competition for arriving first on a result collaboration is still seen as fundamental to reach important goals, is inspiring.

My problem-solving and analytical skills also flourished. I learned how to write a proposal to obtain observing time at large telescopes and this was a great chance to understand what work there is behind the planning of an observational run. I can read almost any paper in the field understanding its goals, give an objective comment, and argue what I would have done in a different way in the analysis. Before the lockdown, I had the opportunity to travel a lot and I gained both national and international experiences in presenting my work to the scientific community and learning new information and technical skills from the major experts in the field, getting to know realities different from the Italian one. My passion for this field, developed during the final year research project in MSc. Degree, aroused during the PhD and helped me to spread my interest towards different sciences related to the topic of exoplanets. I acquired a specific interest on astrobiology and habitability conditions, specifically thanks to my participation at the 2019 Carl Sagan Summer Workshop in Pasadena. I met researchers from other fields, talked to them, and better understood astrobiology and its purposes. I gained a better comprehension of the state of the art in fields other than mine and acquired a general view of the many variables that interact to form a planet like the Earth. After the workshop, I enriched my knowledge reading papers and books, not only strictly connected to the exoplanetary field, but also to the biological, chemical, and geological ones, since I am confident that this will allow me to progress and gain a multi-disciplinary point of view on this fascinating theme.

Before being ready to be a full independent researcher, maybe I still need to be directed somehow, in order to avoid trying to do things that are not feasible. However, after the PhD experience, I am confident that I can start and conduct an analysis in an independent and original way. My knowledge of the exoplanetary field has grown a lot, but has still to improve: in the years to come, I expect to be able to perform runs using the visible and near infrared spectrographs, understand the implications for astrobiology and habitability, and acquire new knowledge in biology, geology, chemistry, and planetary science, since I am aware that future research will necessarily deal with these topics.

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Appendix: KELT-9 b Transmission Spectra

I present here the transmission spectra obtained for KELT-9 b for the individual lines and presented in chapter 7.

A.1 H-alpha

Figure A.1 shows the 2D tomography of $H\alpha$ line.

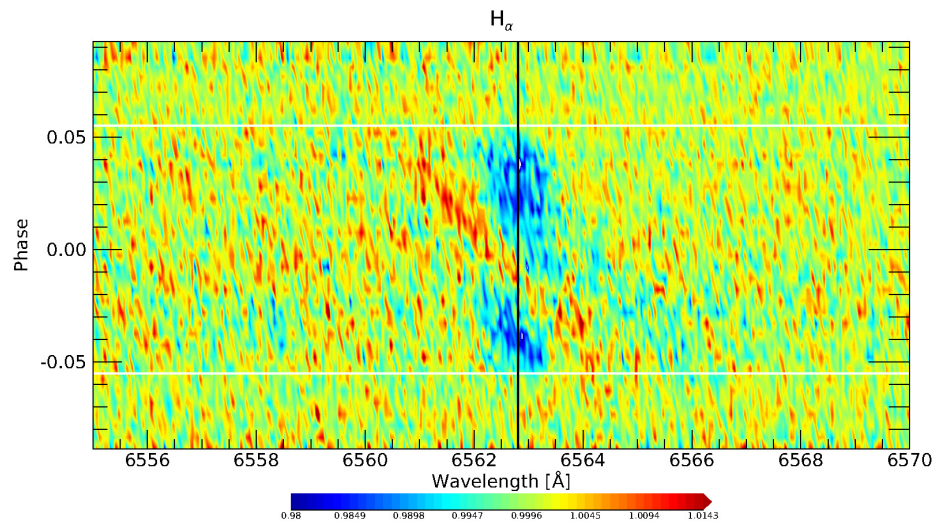


Fig. A.1.: Tomography of $H\alpha$ after analyzing four transits of KELT-9 b. The white solid lines indicate the ingress and the egress of the transit, the black solid line is centered on the $H\alpha$ value (6562.81 $\text{\AA}$).

Figure A.2 shows the transmission spectrum of $H\alpha$ line.

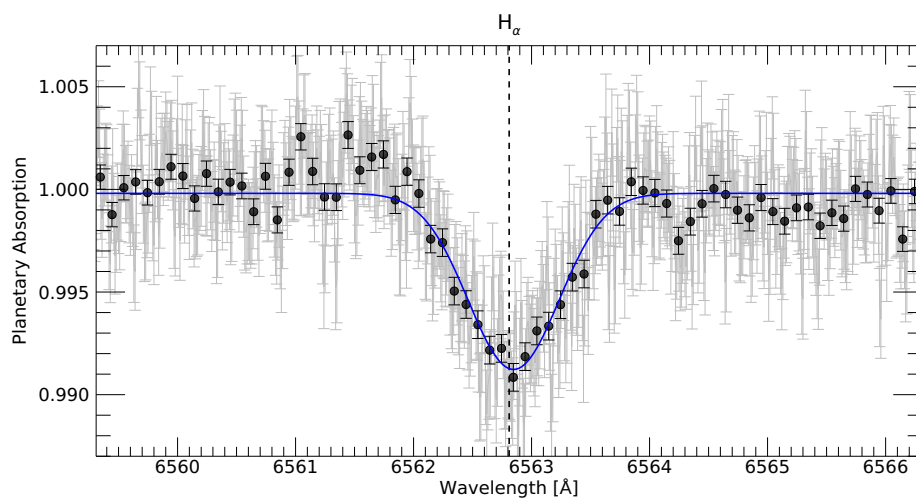


Fig. A.2.: Transmission spectrum of KELT-9 b in the wavelength region of $H\alpha$. The black dashed line is centered on the $H\alpha$ value. The blue line is the Gaussian fit.

A.2 H-beta

Figure A.3 shows the 2D tomography of H β line.

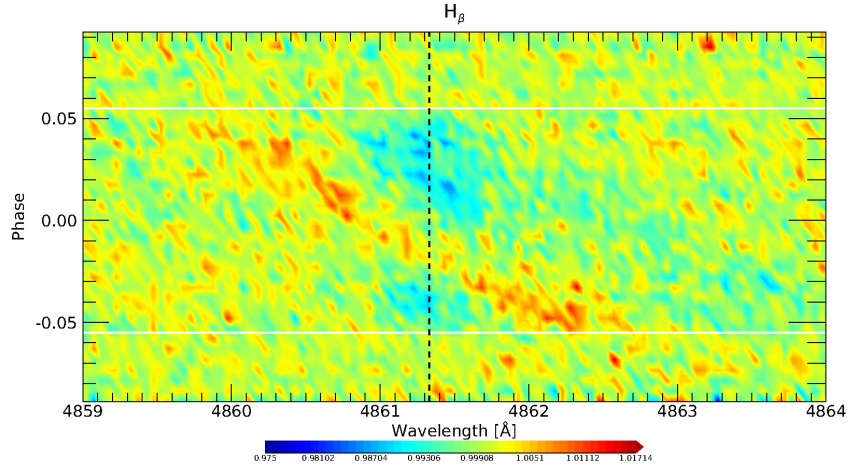


Fig. A.3.: Tomography of H β after analyzing four transits of KELT-9 b. The white solid lines indicate the ingress and the egress of the transit, the black solid line is centered on the H β value (4861.33 Å).

Figure A.4 shows the transmission spectrum of H β line.

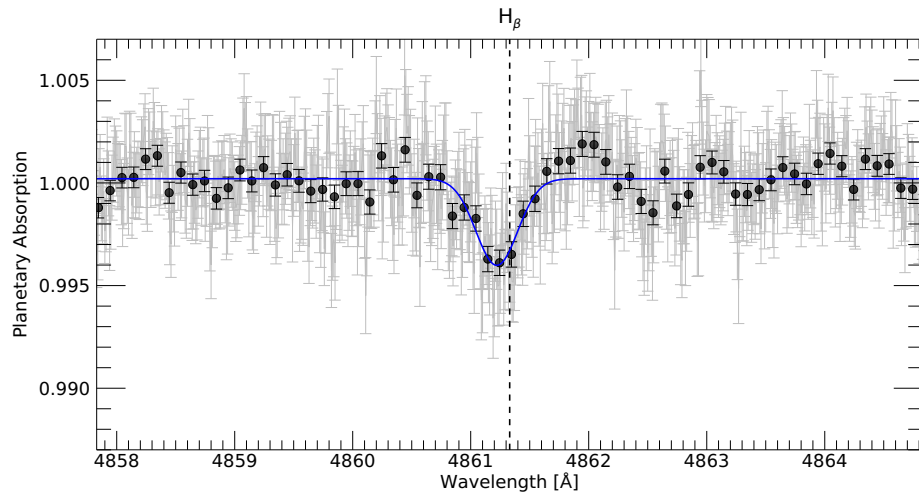


Fig. A.4.: Transmission spectrum of KELT-9 b in the wavelength region of H β . The black dashed line is centered on the H β value. The blue line is the Gaussian fit.

A.3 Na D Doublet

Figure A.5 shows the 2D tomography of Na D₂ and Na D₁ lines.

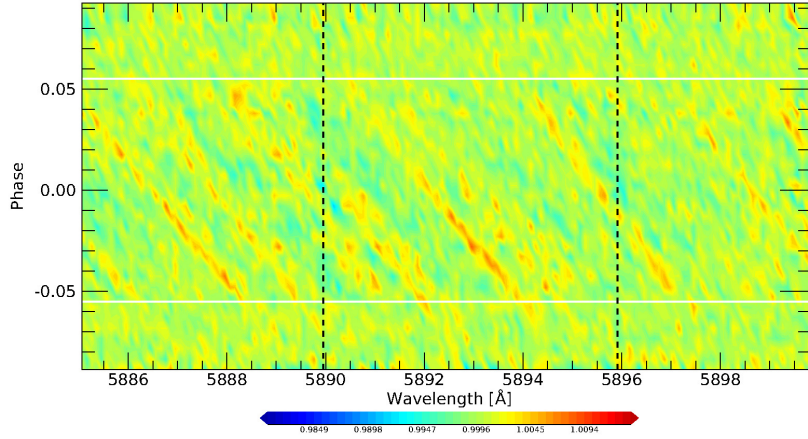


Fig. A.5.: Tomography of Na D₂ and Na D₁ after analyzing four transits of KELT-9 b. The white solid lines indicate the ingress and the egress of the transit, the black dashed lines are centered on the Na D₂ and Na D₁ values (5889.95 Å and 5895.92 Å).

Figure A.6 shows the transmission spectrum of Na D₂ line.

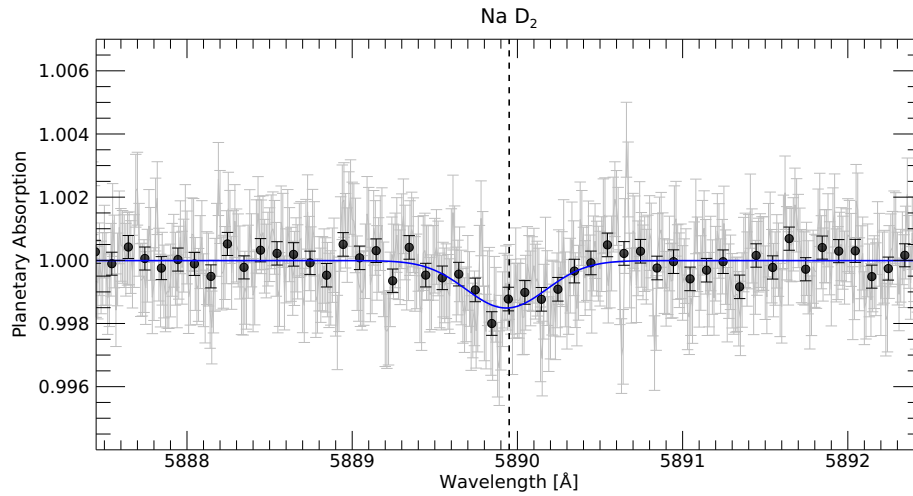


Fig. A.6.: Transmission spectrum of KELT-9 b in the wavelength region of Na D₂. The black dashed line is centered on the Na D₂ value. The blue line is the Gaussian fit.

Figure A.7 shows the transmission spectrum of Na D₁ line.

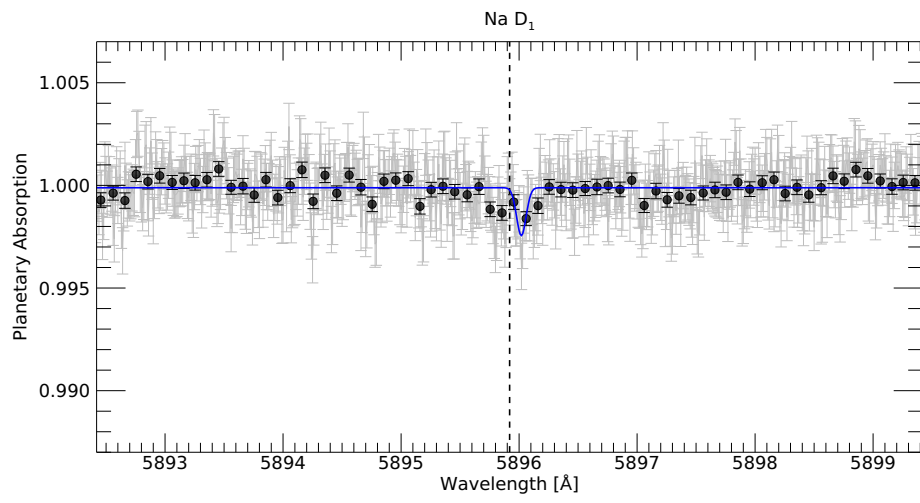


Fig. A.7: Transmission spectrum of KELT-9 b in the wavelength region of Na D₁. The black dashed line is centered on the Na D₁ value. The blue line is the Gaussian fit.

A.4 Fe II

The 2D tomography of Fe II line (5169.03 Å) is shown in Chapter 7 as part of the main analysis, since this line is very close to the first line of the Mg I triplet.

Figure A.8 shows the transmission spectrum of Fe II line.

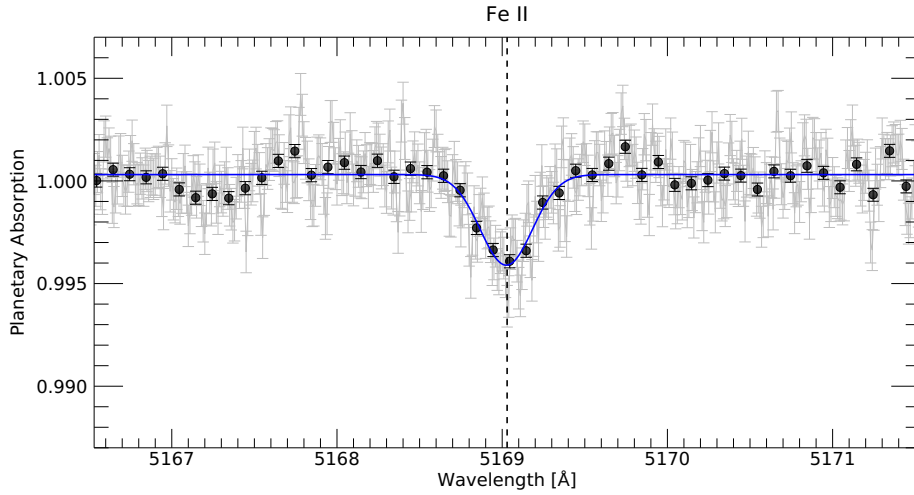


Fig. A.8.: Transmission spectrum of KELT-9 b in the wavelength region of $H\beta$. The black dashed line is centered on the $H\beta$ value. The blue line is the Gaussian fit.

Appendix: KELT-20 b Transmission Spectra

I present here the transmission spectra obtained for KELT-20 b for the individual lines and presented in chapter 7.

B.1 H-alpha

Figure B.1 shows the 2D tomography of $H\alpha$ line.

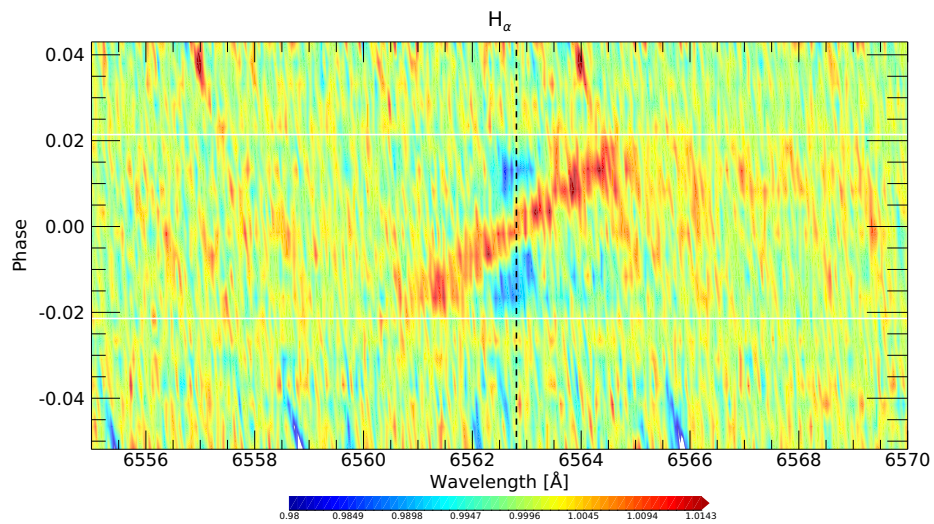


Fig. B.1.: Tomography of $H\alpha$ after analyzing four transits of KELT-20 b. The white solid lines indicate the ingress and the egress of the transit, the black solid line is centered on the $H\alpha$ value (6562.81 $\text{\AA}$).

Figure B.2 shows the transmission spectrum of $H\alpha$ line.

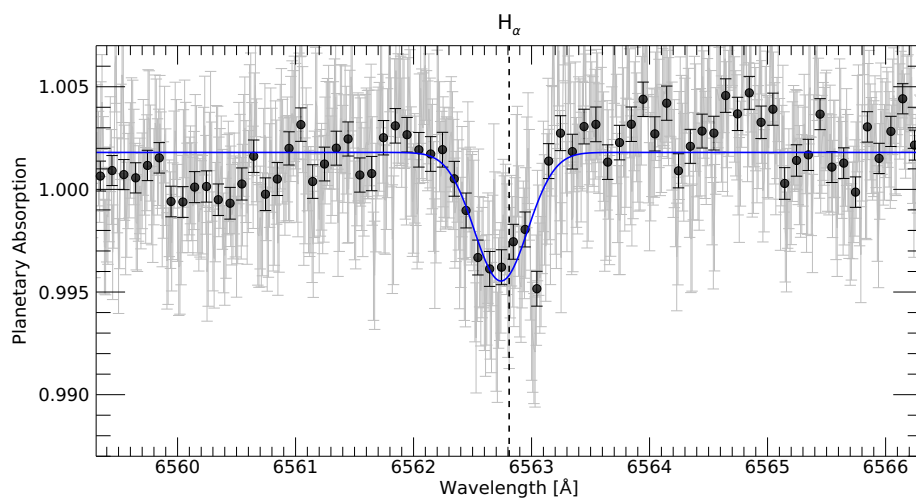


Fig. B.2.: Transmission spectrum of KELT-20 b in the wavelength region of $H\alpha$. The black dashed line is centered on the $H\alpha$ value. The blue line is the Gaussian fit.

B.2 H-beta

Figure B.3 shows the 2D tomography of H β line.

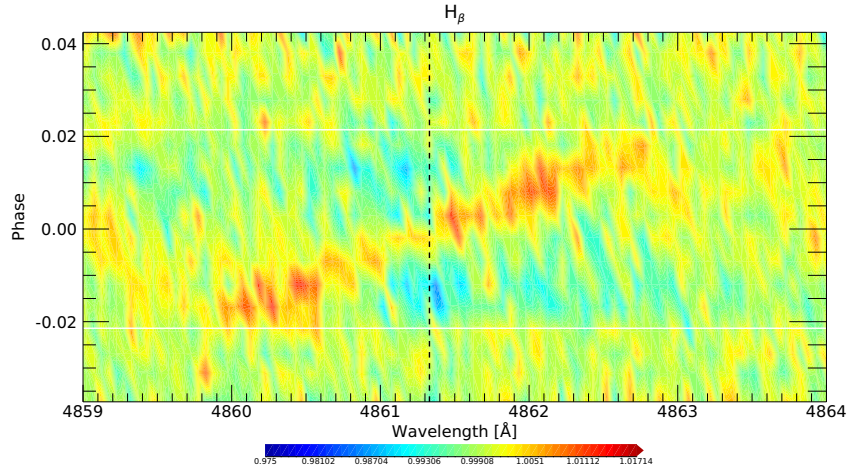


Fig. B.3.: Tomography of H β after analyzing four transits of KELT-20 b. The white solid lines indicate the ingress and the egress of the transit, the black solid line is centered on the H β value (4861.33 Å).

Figure B.4 shows the transmission spectrum of H β line.

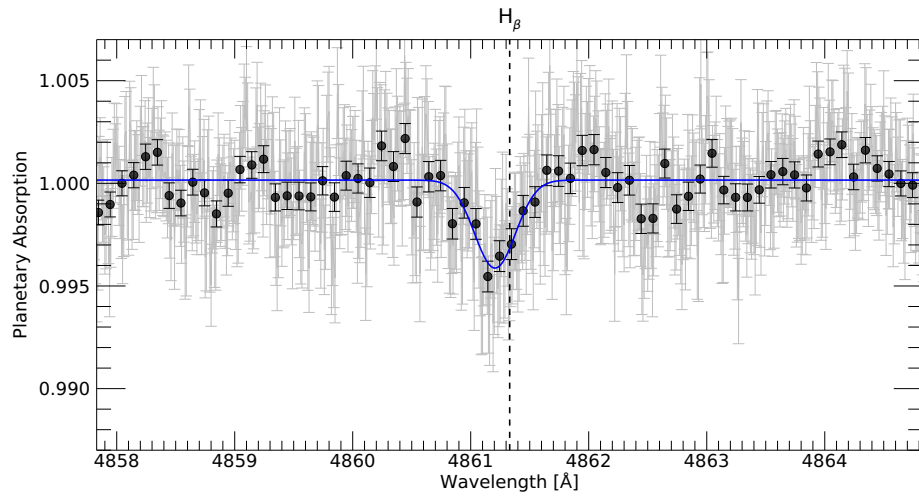


Fig. B.4.: Transmission spectrum of KELT-20 b in the wavelength region of H β . The black dashed line is centered on the H β value. The blue line is the Gaussian fit.

B.3 Na D Doublet

Figure B.5 shows the 2D tomography of Na D₂ and Na D₁ lines.

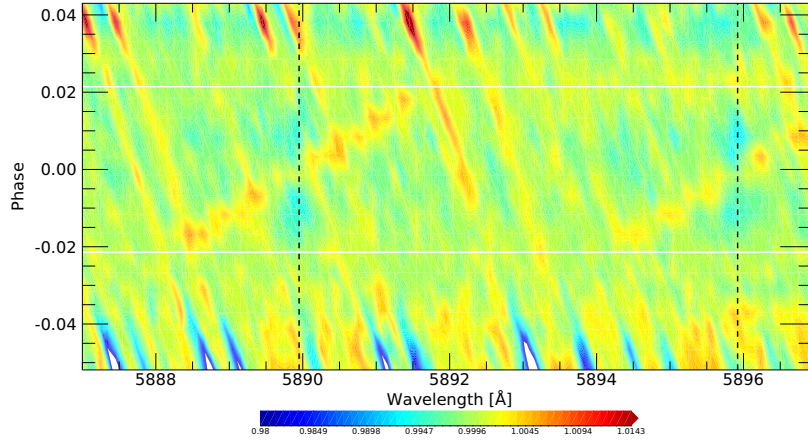


Fig. B.5.: Tomography of Na D₂ and Na D₁ after analyzing four transits of KELT-20 b. The white solid lines indicate the ingress and the egress of the transit, the black dashed lines are centered on the Na D₂ and Na D₁ values (5889.95 Å and 5895.92 Å).

Figure B.6 shows the transmission spectrum of Na D₂ line.

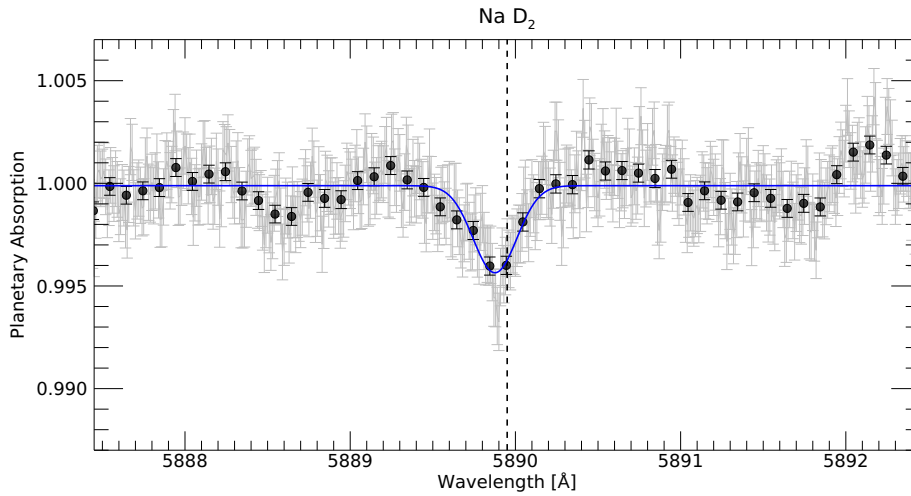


Fig. B.6.: Transmission spectrum of KELT-20 b in the wavelength region of Na D₂. The black dashed line is centered on the Na D₂ value. The blue line is the Gaussian fit.

Figure B.7 shows the transmission spectrum of Na D₁ line.

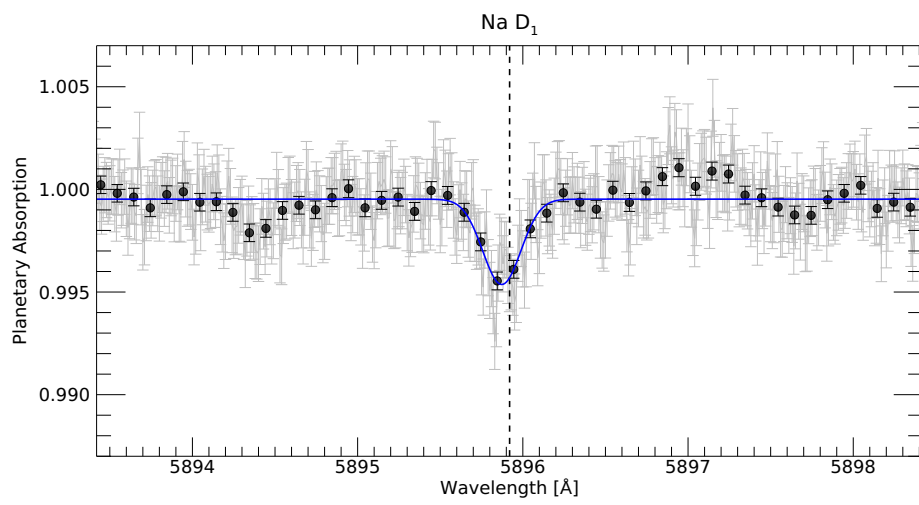


Fig. B.7.: Transmission spectrum of KELT-20 b in the wavelength region of Na D₁. The black dashed line is centered on the Na D₁ value. The blue line is the Gaussian fit.

B.4 Fe II

The 2D tomography of Fe II line (5169.03 Å) is shown in Chapter 7 as part of the main analysis, since this line is very close to the first line of the Mg I triplet.

Figure B.8 shows the transmission spectrum of Fe II line.

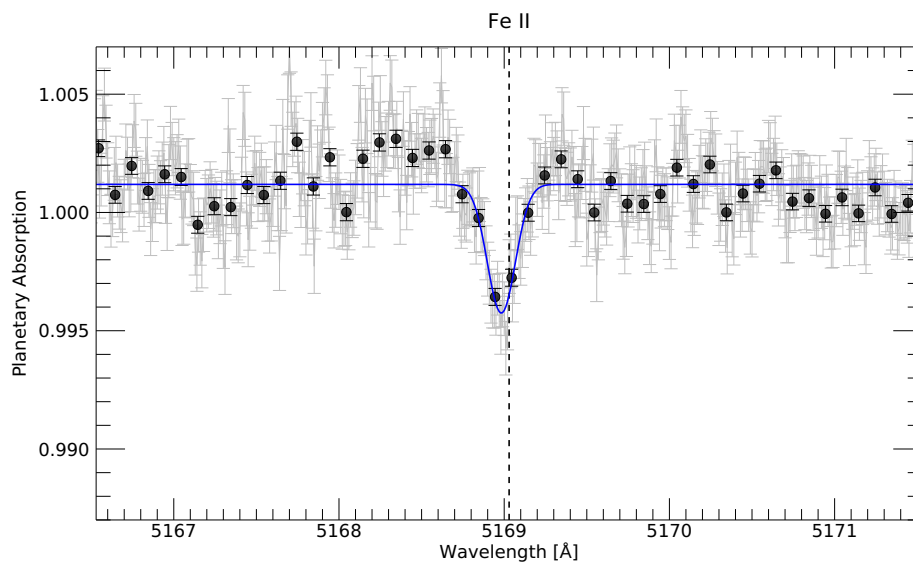


Fig. B.8.: Transmission spectrum of KELT-20 b in the wavelength region of $H\beta$. The black dashed line is centered on the $H\beta$ value. The blue line is the Gaussian fit.

