Detection and Characterization of Transiting Extrasolar Planets: Expanding the Parameter Space

by

RAFAEL ANDRÉS BRAHM S.

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ADVISOR:
Dr. Andrés Jordán (PUC)

READERS:
Dr. Márcio Catelan (PUC), Dr. Subo Dong (KIAA-PKU), Dr. Manuela Zoccali (PUC)

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Dedicado a Renate y Simón.
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Abstract

After twenty years of numerous and interesting discoveries in the field of extrasolar planets, the study of these systems is turning from the mere detection of new objects towards their detailed characterisation, with the goal of testing theories of formation, structure and evolution of exoplanets. In this context, transiting extrasolar planets orbiting bright stars are especially interesting objects of study because a great amount of physical and orbital parameters can be inferred from them, which are currently impossible to be estimated if the orbital plane is not aligned with our line of sight. The current sample of transiting extrasolar planets that are amenable for characterisation is strongly biased due to several observational effects. Most of these objects are Jupiter-sized planets orbiting very close to their host stars with periods shorter than 10 days. In order to have a clearer picture of the properties of extrasolar planets it is required to expand the parameter space of this kind of systems by discovering objects with longer periods and smaller radii.

With this goal in mind, the HATSouth project is a ground based photometric survey dedicated to the detection of transiting extrasolar planets and was specifically designed to detect systems in regions of the parameter space that are sparsely populated. In this thesis I describe the machinery that was developed to process and analyse most of the follow-up spectroscopic data of transiting extrasolar planetary candidates discovered by the HATSouth survey and I also
report the discovery of three systems that were confirmed thanks to these spectroscopic tools. One of the systems is the exoplanet with the longest detected period from the ground with $P=16$ d, a full 6 d longer than the previous record holder with $P=10$ d. We are thus starting to harvest the interesting systems HATSouth set out to discover.
Resumen

Tras 20 años de numerosos e interesantes descubrimientos en el campo de planetas extrasolares, el estudio de estos sistemas está virando desde la mera detección de nuevos objetos hacia su caracterización detallada, con el propósito de probar teorías de formación, estructura y evolución de exoplanetas. En este contexto, los planetas extrasolares transitan son objetos especialmente interesantes ya que, para este tipo de sistemas, una gran cantidad de parámetros físicos y orbitales pueden ser inferidos, los cuáles son imposibles de estimar si es que el plano orbital no se encuentra alineado con nuestra línea de visión. La muestra actual de planetas extrasolares transitan adecuados para ser caracterizados está fuertemente sesgada debido a varios efectos observacionales. La mayoría de estos objetos son planetas del tamaño de Júpiter con órbitas muy cercanas a su estrella huésped con periodos más cortos de 10 días. Para tener una imagen más clara acerca de las propiedades de los exoplanetas se requiere expandir el espacio de parámetros para este tipo de sistemas a través del descubrimiento de objetos con períodos más largos y radios menores.

Con esta meta en mente, el proyecto HATSouth es un survey fotométrico dedicado a la detección de planetas extrasolares transitan y fue diseñado específicamente para detectar sistemas en regiones del espacio de parámetros que se encuentran solo escasamente pobladas. En esta tesis describo toda la maquinaria que fue desarrollada para procesar y analizar la mayoría de los datos
espectroscópicos de seguimiento de candidatos a planetas extrasolares transitantes descubiertos por el proyecto HATSouth y además reporto el descubrimiento de tres sistemas que fueron confirmados gracias a estas rutinas espectroscópicas. Uno de estos sistemas corresponde al exoplaneta con el período más largo detectado desde la tierra con \( P = 16 \) d, 6 días completos más largo que el que poseía el record anterior con \( P = 10 \) d. De esta manera estamos comenzando a cosechar los sistemas interesantes que HATSouth se ha propuesto a descubrir.
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Chapter 1

Introduction

Twenty years ago, a key mystery about our universe was solved. The discovery of 51Pegb (Mayor & Queloz 1995), the first extrasolar planet orbiting a normal star, proved that the Sun was not the only star that harbours a planetary system. Since then, thanks to the development of new instrumentation and observing techniques, about 1900 exoplanets have been detected and the principal statistical conclusion of these discoveries is that probably, there are more planets than stars in our galaxy, which certainly changes our perspective of position and life in the universe. However, as usually happens in science, these discoveries brought many more unsolved mysteries about the formation, structure and evolution of planetary systems.

Before 1995, the classical nebular theory of the formation of planetary systems had been developed to fit the available data. This means that it was able to explain most of the properties of our solar system: all planets have almost circular and coplanar orbits; there are two clearly separated types of planets, namely gas giants and terrestrial, and gas giants are only found at large separations (a > 5 AU) from their central star.

The challenges to the classical theory started to appear with the first discovered exoplanet.
51Pegb was a Jupiter-mass planet orbiting extremely close to its host star at only $a \sim 0.05$ AU. This exoplanet was discovered with the radial velocity (RV) method (see Section 1.1.1). The properties of the new planet were clearly not expected and caused initial scepticism in the astronomical community. Many argued that the signal observed in the star 51Peg could be produced by an unknown type of stellar pulsation. The general acceptance of the planetary nature of systems like 51Pegb was only attained when some of them started to show measurable eccentricities in their orbits and also when one of them was photometrically monitored while eclipsing its host star (Charbonneau et al. 2000). Due to their extremely high insolation levels, these kinds of planets were termed hot Jupiters and their origin is still a matter of active scientific debate. Posterior discoveries showed also that there is a vast diversity of exoplanets in terms of their orbital parameters and physical structure, with many of them having properties not found in our solar system.

In order to develop new theories able to explain the properties of exoplanets and to put our own planet in a broader perspective we still need to discover new planetary systems, but as importantly, we need to accurately characterise them for determining which observational properties and/or mechanisms can be linked with theoretical models.

1.1 Detection Techniques

The different detection techniques give us different information about the discovered planets. Even though there are five techniques that have been successful in discovering new extrasolar planets, the two techniques that have allowed to most significantly increase the sample of known systems are the radial velocity method and the transit method.
1.1.1 The Radial Velocity Method

Observables

The gravitational interaction between the planet and the host star causes the star to describe an elliptical orbit around the centre of mass of the system, which produces a periodical change of the position and velocity vectors of the star. The component of the velocity vector parallel to the observers’ line of sight (the radial component) can be measured by obtaining spectra of the star at different epochs and determining the Doppler shifts of the absorption lines. The periodical variation of the radial velocity of a star can be associated with the presence of an orbital companion and the exact shape and amplitude of the radial velocity curve will depend on the mass of the star, the mass of the orbital companion and the orbital parameters of the system. By using the Newton’s laws of motion and Kepler’s third law, we obtain that the radial velocity signal of the star produced by one orbital companion is:

\[ v_r = K[\cos (\omega + \nu(t)) + e \cos \omega], \]  

(1.1)

where \( e \) is the orbital eccentricity, \( \omega \) is the argument of the pericentre and \( \nu \) is a time dependent angle, measured from the direction of the pericentre to the current position of the planet, called the true anomaly. In equation 1.1, \( K \) is the radial velocity semi-amplitude given by:

\[ K = \left( \frac{2\pi G}{P} \right)^{1/3} \frac{M_p \sin i}{(M_* + M_p)^{2/3}} \frac{1}{(1 - e^2)^{1/2}}, \]  

(1.2)

where \( G \) is the gravitational constant, \( P \) is the orbital period, \( M_p \) is the mass of the orbital companion, \( M_* \) is the mass of the star and \( i \) is the inclination of the orbit with respect to the line of sight. While \( P \) and \( e \) can be independently determined from the periodicity and shape of the velocity signal, the measurement of \( K \) can be used to determine a lower limit for the companions’ mass (\( M_p \sin i \)) if the mass of the star is known.
Radial Velocities Planet Yield

To date, 470 extrasolar planets have been discovered by using the radial velocity technique. The minimum mass of these objects is plotted as function of their semi-major axes in figure 1.1. These discoveries have been fundamental for determining statistical properties of planetary systems. Marcy et al. (2008) and Udry & Mayor (2008) concluded that the fraction of giant planets within $\sim 5$ AU is $\sim 10\%$, while Marcy et al. (2008) also found that the distribution of minimum masses rises with decreasing mass at least until Neptune-mass planets following a power law. Regarding the period distribution of radial velocity exoplanets, it extends from less than one day to $5 \times 10^3$ days and it is mostly concentrated at $P > 100$ days.

An important conclusion obtained from the sample of RV planets is that, as opposed to the solar system, most exoplanets have measurable eccentricities. The median eccentricity of planets with orbital periods longer than 6 days is 0.3 and some of these planets can even reach $e \sim 0.9$.

Systems with more than one planet orbiting a star have been also detected with the radial velocity method. Around 20% of the RV planets belong to multi-planetary systems, which can be used to test theories about the stability, interaction and migration of extrasolar planets.

1.1.2 The Transit Method

While the RV method has been very useful for obtaining statistical conclusions about the occurrence and orbital properties of exoplanets, generally these systems cannot be characterized in detail. On the other hand, the amount of information that can be extracted from transiting systems is enormous. The transit method is based on the measurement of the fraction of stellar light that is blocked by a planet whose orbital plane is approximately aligned with the observers’ line of sight. The detection of periodical dips in the light-curve of a star can be associated with the
Figure 1.1: Minimum mass as function of the semi-major axis for extrasolar planets discovered by the RV method. If observational biases are taken into account, these discoveries show that giant planets are preferably found with $a > 1$ AU and with non zero eccentricity.

The presence of an orbital companion and the exact shape of the transit signal can be used to obtain important physical and orbital parameters of the planet. Figure 1.2 shows an artificial transit light-curve and the 4 observables that can be extracted from it. $\Delta F$ is the faction of the stellar flux blocked by the transiting planet, $P$ is the orbital period, $t_F$ is the total duration of the transit from first to fourth contact and $t_E$ is the partial duration of the transit after the ingress and before the egress. By using geometry and Kepler's laws, these four observables can be linked to five parameters of the system by the following equations:

$$\Delta F = \left( \frac{R_p}{R_*} \right)^2 ;$$  \hspace{1cm} (1.3)
Figure 1.2: Diagram of the geometry of a transiting system and its corresponding observables. Figure taken from The Exoplanet Handbook (Perryman 2011).

\[
\frac{t_F}{t_T} = \frac{\arcsin \left( \frac{R_*}{a} \left[ \frac{(1 + \frac{R_p}{R_*})^2 - \left( \frac{R_p}{R_*} \cos i \right)^2}{1 - \cos^2 i} \right]^{1/2} \right)}{\arcsin \left( \frac{R_*}{a} \left[ \frac{(1 + \frac{R_p}{R_*})^2 - \left( \frac{R_p}{R_*} \cos i \right)^2}{1 - \cos^2 i} \right]^{1/2} \right)}; \tag{1.4}
\]

\[
t_T = \frac{P}{\pi} \arcsin \left( \frac{R_*}{a} \left[ \frac{(1 + \frac{R_p}{R_*})^2 - \left( \frac{a}{R_* \cos i} \right)^2}{1 - \cos^2 i} \right] \right); \tag{1.5}
\]

\[
P^2 = \frac{4\pi^2 a^3}{G(M_* + M_p)} . \tag{1.6}
\]
Chapter 1. Introduction

The principal parameter that can be inferred from transiting systems is the radius of the planet if the radius of the star is known. We can also determine the inclination of the orbit from the light-curve which allows us to compute the true mass of the planet if RV measurements are available and if the mass of the star is known. The radius estimate coupled with the mass of the planet can be used to determine its bulk density which, coupled to theoretical models, allows us to infer its physical structure and composition.

Characterisation of TEPs

TEPs are true laboratories in which theories of formation, structure and evolution of extrasolar planets can be tested with great detail. One of the most direct properties that can be inferred from particular TEPs is their bulk composition. The composition of terrestrial planets can be inferred by fitting their measured mass and radius to theoretical models (Zeng & Sasselov 2013), while in the case of giant planets, structural models can be used to infer the mass of the central solid core and the mass of the H/He envelope (e.g. Fortney et al. 2007; Burrows et al. 2007).

It is also possible to study the properties of the atmospheres of TEPs using different techniques. The observation of secondary transits and phase curves in the visible and infrared can be used to obtain information about the reflection and emission properties (e.g. Madhusudhan & Seager 2011; Kammer et al. 2015). The presence of particular atoms and molecules in the atmosphere of TEPs can be determined by obtaining the transit light-curve at different wavelengths. These absorbers will block more light of the star in distinct zones of the spectrum and the transit depth will become greater at those wavelengths (e.g. Redfield et al. 2008; Fraine et al. 2014). This same technique, known as transmission spectroscopy, can be used to measure the Rayleigh scattering in the atmosphere of the planet, which is related to its mean molecular weight (e.g. Jordán et al. 2013; Sing et al. 2015).
TEPs can also be used for characterizing their orbital geometries, because the sky-projected misalignment angle between the spin of the star and the orbital plane, known as obliquity, can be measured. This is possible due to the fact that as the planet transits its star, it blocks zones with different rotation component in the radial direction which produces an anomaly in the shape of the absorption lines of the stellar spectrum. There are two techniques for computing the obliquity. The most common one is known as Rossiter-McLaughlin effect (Rossiter 1924; McLaughlin 1924) and is based on the measurement of precise RV variations during transit. The effect of the planet blocking different zones of the star will be observed as an anomalous RV signal and the shape of this signal depends on the projected rotational velocity of the star and on the orbital obliquity (e.g. Zhou et al. 2015b). The second technique, known as Doppler tomography, is applicable only on fast rotators and is based on actually measuring the blocked signal of the planet at different velocities from the absorption lines of the stellar spectrum (e.g. Collier Cameron et al. 2010; Hartman et al. 2015a).

**Ground-based transit surveys**

One of the major drawbacks for detecting transiting planets is the fact that the transit probability is quite low and strongly depends on the orbital separation as:

$$ p = \left( \frac{R_*}{a} \right) \frac{1}{1 - e^2}. $$

(1.7)

For this reason, in order to detect a substantial number of planets, photometric surveys must monitor a great number of stars in wide fields of view which can be achieved with small aperture telescopes (~ 20 cm) from the ground. Given that variations in the stellar flux produced by the atmosphere are orders of magnitude greater than the change in flux due to a transiting planet, the photometry must be performed differentially with respect to other stars in the field.
One of the most important requirements for discovering transiting planets from the ground is the high duty cycle needed for measuring several periodical dips in the light-curves in order to build a large enough detection signal. In order to achieve a reasonable detection yield, observations must be performed constantly, as much as the weather and diurnal cycle allows. Robotic telescopes have played a key role in the detection of transiting planets from the ground by obtaining homogeneous, good-quality data at low cost, while at the same time avoiding the use of valuable human time in monotonous technical operations.

There are currently \( \sim 180 \) TEPs discovered by automated ground-based photometric surveys. The most successful ones are the Super Wide Angle Search for Planets (Pollacco et al. 2006, SuperWASP) with 105 discoveries and the Hungarian Automated Telescope Network (Bakos et al. 2004, HATNet) with 53 discoveries, while other \( \sim 20 \) TEPs have been discovered by other projects, namely: KELT (Pepper et al. 2007), TRES (Alonso et al. 2004), XO (McCullough et al. 2005), QATAR (Alsubai et al. 2013) and MEarth (Irwin et al. 2009).

A valuable property of the TEPs discovered by these ground-based transit surveys is that they orbit bright or moderately bright stars \((V<13)\), which allows the measurement of precise RVs for confirming the planetary nature of the transiting body. These RV measurements allow also to determine the mass and bulk density of the planet. The brightness of these host stars also permit detailed follow-up studies to further characterise the systems improving our knowledge about the formation and structural composition of exoplanets and planetary systems.

Ground-based photometric transit surveys are strongly biased to discover giant planets \((R_p > 0.8 \, R_J)\) with short orbital periods \((P < 8 \text{ days})\). For this reason, as is shown in Figure 1.3, the vast majority of the planets discovered by these surveys are hot Jupiters. The first observational constraint originates from (1) the small aperture of the used telescopes that affects the precision of the derived light-curves and (2) the existence of correlated (red) noise in the photometric
time series, which can arise due to different sources: changes in the atmosphere, variations in the properties of the environment, changes in the instrumental properties, among others. The second observational constraint is mostly related to the high duty cycle required to build high enough SNR light-curves to detect long-period (P>10 days) planets. Given that most of these surveys have stations located in only one geographical latitude, the gaps in the data produced by the diurnal cycle produce the loss of the transits required to increase the SNR of the detection.

**Space missions**

One possibility for discovering extrasolar planets with smaller sizes and/or longer periods than the ones found by ground-based surveys is to develop space-based missions. The photometric precision achievable in the absence of an atmosphere allows the detection of earth-size planets around solar type stars, and the continuous photometric monitoring translates into a high duty cycle required to recover long period planets. The two missions that were specifically designed to discover TEPs from space so far are CONvection ROTation and planetary Transits (Bagnin et al. 2006, COROT) and Kepler (Borucki et al. 2010).

The COROT satellite was launched at the end of 2006 and collected data for almost 3 years. It was designed to detect TEPs down to a few earth radii with periods shorter than 75 days. However, most of the ~30 confirmed planets detected by COROT were hot Jupiters. Some particular exceptions were COROT-7b (Léger et al. 2009) and COROT-22b (Moutou et al. 2014), having $M_p < 0.05 \, M_J$; and COROT-9b (Deeg et al. 2010), having an orbital period of 95 days.

Even though COROT was the first space mission capable of detecting TEPs with small radii, the Kepler mission was responsible for significantly increasing the number of this type of systems, making possible a census of the occurrence and distribution of extrasolar planets with different properties in our galaxy. The Kepler satellite was launched at the beginning of 2009 and per-
formed continuous monitoring of 145,000 stars in a fixed field of view with a diameter of 12
deg located in the northern hemisphere for ~3.5 years, before one of its four reaction wheels
failed. To date, 1030 TEPs discovered by Kepler have been confirmed or validated, while there
are 4696 candidates. The main results of the Kepler mission are:

- There are at least as many planets as stars in our galaxy (Swift et al. 2013).

- Giant planets are significantly less numerous than terrestrial and subneptune-mass plan-
et. In particular the study of Rowe et al. (2014) presented 715 new validated planets
were 95% of them where smaller than Neptune.

- Earth-like planets are abundant in our galaxy. The exact fraction of earth-like planets
will depend on the definition of habitable zone, but several studies have estimated that
the fraction of stars that harbour Earth-like planets ranges from 1.7% (Foreman-Mackey
et al. 2014) to 48% (Kopparapu 2013).

One of the problems of the TEPs discovered by Kepler is that they orbit stars that are generally
fainter (V>14) than the hosts of TEPs discovered from the ground. This fact translates in that
the confirmation via RV measurements and the determination of the masses of these planets
is possible only for a minor fraction of the systems (~70 in total). For this same reason, the
detailed follow-up observations that can be performed on TEPs to characterise their orbital
geometry and their atmospheric properties cannot be performed in general on the systems
discovered by Kepler.
1.2 Giant Planets

Even though giant planets (GPs) are much less numerous than rocky planets, they are very important objects of study. One reason is that, due to their high masses, it is expected that these objects govern the fate of the smaller planets in their planetary systems. For example, in the case of our own solar system, the gravitational perturbation of Jupiter in the orbit of the Earth drives the Milankovitch cycles, which are thought to be responsible of producing the ongoing series of glacial and interglacial periods that control the climate and the habitable conditions of our planet. The actual orbital parameters of Jupiter produce a relatively small effect on the terrestrial planets, however from numerical simulations it has been inferred that slight changes in the semi-major axis or eccentricity of Jupiter can make the interior planets of the solar system become unstable, significantly modifying their orbital parameters and producing even the crossing of their orbits (Horner et al. 2015). In other planetary systems, the interactions between giant planets and minor bodies could be much more catastrophic, implying ejections from the system or collisions with other planets or with the central star, which could arise for example if the giant planet is experiencing a migration process or after suffering a close encounter with another giant planet.

Another interesting property of giant planets is that, as was mentioned in section 1.1.2, they can be efficiently detected from the ground using relatively cheap instrumentation, which allows to form a relatively large sample of objects that can be then used to identify correlations and trends in their properties. These correlations can then be contrasted with different theories of formation, structure and evolution. Moreover, the large masses and sizes of these objects produce observational signals that are strong enough to be detected with current astronomical technology and allows to characterize the individual systems in great detail.
Currently, the best characterized type of extrasolar planets are the transiting hot Jupiters. With more than 200 systems known, some important properties of the population have started to be established, but, most of these properties are lacking accepted theoretical explanations.

![Graph showing planetary radius vs. planet mass](image)

**Figure 1.3:** Discovered transiting extrasolar planets with measured radii and masses. Most giant planets have been discovered from ground-based photometric surveys, while most sub-Neptune sized planets have been detected by the Kepler mission.

As is shown in figure 1.3, an evident property of the sample of well characterized transiting extrasolar planets is that there is an absence of planets with masses between Neptune and half the one of Saturn compared to terrestrial and Jupiter mass planets. It is not clear if this valley is due to a real underlying physical cause or if it is produced by an observational selection effect, because common ground-based surveys are insensitive to such small planets which at the same time are in the low occurrence rate tail of space-based missions. In several works (e.g.}
Mordasini et al. 2011, 2015), the lack of super-Neptunes is explained from a theoretical point of view by running population synthesis of extrasolar planets. In these simulations it is found that when the embryos have accreted enough material, they start a runaway process of gaseous accretion which terminates when the planet has accreted all the material in its neighborhood, generating a planet that is probably more massive than Saturn. Clearly, a systematic search of planets with sub-Saturn masses is required to test this hypothesis.

As will be described in Chapter 5, other theoretical challenges regarding giant planets are related to (1) the presence of some of them at short orbital distances ($0.01 AU < a < 1 AU$) which is linked to different migration mechanisms that can operate; and (2) the wide variety of planetary radii for a given mass, where many close-in giant planets are highly inflated reaching radii even twice as large than predicted by theoretical models. Both of these issues could be tackled by the detection and characterisation of TEPs with larger orbital distances and lower insolation levels and longer periods.

Finally, most of the transiting giant planets have been discovered around FGK-type stars because ground-based surveys are mostly sensitive to these types of planetary hosts. From one side, the atoms in the atmospheres of earlier-type stars are strongly ionised and therefore the confirmation of candidates via RVs is commonly an impossible task. On the other hand, the instruments used by typical ground-based photometric surveys can only target bright stars ($V<11$), and given the intrinsic faintness of M-dwarfs in the optical, a very limited number of M-dwarfs is usually monitored by these projects. These low-mass stars are not expected to possess disks massive enough to build Saturn or Jupiter mass planets (Rodriguez et al. 2015), but this claim must be tested with a systematic search of giant planets orbiting M-dwarfs or lower mass stars.
1.3 The HATSouth survey

As was mentioned in the previous sections, TEPs offer the possibility of studying particular exoplanetary systems with great detail by allowing the estimation of valuable physical and orbital parameters, which if used in a broader context are fundamental for constraining theories of structure, formation and evolution of exoplanets.

However, one of the limitations of the current sample of discovered TEPs is that, as is shown in Figure 1.3, they are clustered in a relatively small region of the parameter space. Due to observational biases of ground-based photometric surveys, most of the well characterized TEPs are Jupiter-sized planets orbiting at very close distances ($a \approx 0.03$ AU) from their parent stars. On the other hand, most of the numerous TEPs discovered from space, which occupy a much more extensive region of the parameter space, orbit stars that are generally too faint for allowing follow-up studies to further characterise those objects.

In this context, the Hungarian Automated Telescope South (HATSouth, Bakos et al. 2013) survey was developed with the goal of expanding the parameter space of characterisable TEPs by detecting new types of systems from the ground. The HATSouth survey photometrically monitors selected fields of the sky for $\sim 3$ months each, with a cadence of four minutes and looks for periodical dips in the light curves that can be produced by TEPs. HATSouth is the world's first network of automated and homogeneous telescopes, with three sites in the southern hemisphere (Las Campanas Observatory in Chile, HESS site in Namibia, and Siding Spring Observatory in Australia), capable of performing non-stop observations during the entire year. Each of the three stations is equipped with two HATSouth units, each containing four 0.18m diameter f/2.8 focal ratio telescope tubes on a common mount producing a $8.2^\circ \times 8.2^\circ$ field-of-view on the sky, imaged using four 4K×4K CCD cameras and Sloan $r$ filters, to give a pixel scale of
3.7"/pixel\(^{-1}\). Each unit is completely automated and robotic and needs no human intervention. They are equipped with weather and ambient sensing devices which determine if the domes can be opened.

The principal novelty of HATSouth compared to other similar surveys is that the use of its three sites substantially increases the duty cycle, which is mandatory for discovering TEPs with longer periods (P > 10 days). Based on simulations, Bakos et al. (2013) show that with its complete configuration, the probability of recovering TEPs with periods of 15 days is of order ~20\%, which is substantially higher than the probability that single site surveys have for discovering P~8 days TEPs. This is quite encouraging given that single site surveys have already discovered some P~10 days planets. Its high duty cycle coupled to its relatively large telescope apertures also increases the probability of HATSouth for detecting transits as shallow as 1 – 5 mmag. Depending on the properties of the particular stellar hosts, the depth of those transits could be produced by Neptune and even super-earth sized planets. HATSouth is primarily designed to discover TEPs around bright stars (V < 13); however, due to the increased aperture of its telescopes as compared to the ones of the HATNet and WASP projects, HATSouth is also sensitive to monitor moderately fainter stars (13 < V < 16). This extension in the limiting magnitude allows HATSouth to have an increased probability of detecting TEPs around M-dwarf stars.

Aperture photometry is applied on all the stars in each field and the constructed light-curves are corrected from systematics using the External Parameter Decorrelation and the Trend Filtering Algorithm routines (Bakos et al. 2010). Periodical transit-like signals are identified using the Box Least Squares algorithm (Kovács et al. 2002) to select the TEP candidates.
1.3.1 False Positives

There are other astrophysical systems that can produce periodical transit-like signals in their light-curves. These systems are called false positives and can be conformed by a dwarf star eclipsing a giant star, a brown dwarf eclipsing a main sequence star and a diluted eclipsing binary, where a background star contaminates the light-curve of an eclipsing binary reducing the depths of the eclipses. For this reason, in order to confirm the planetary nature of transiting systems, posterior follow-up observations are required. The most direct method is to acquire spectroscopic data of the stellar host. The spectra can be used to characterise the star and the identification of more than one stellar component is used to reject blended systems. In addition, the measurement of RV variations in phase with photometric ephemeris reveals that the transits are produced by an orbital companion and the amplitude of the variation determines if it has a planetary mass. This procedure is commonly applied to confirm TEPs orbiting relatively bright stars, but when the mass of the planet is too small to be measured from RV variations or when the host star is too faint, the system can be statistically validated. This technique compares the probability of the planetary hypothesis against that of all reasonably conceivable alternative false-positive hypotheses and includes a detailed analysis of the light-curves and also other follow-up observations like high resolution images obtained with adaptive optics or lucky imaging (Díaz et al. 2014).

In the case of the HATSouth survey, the number of false positives is quite low if it is compared to typical rates of other ground-based transiting surveys. Its pixel-scale of ~4"pixel$^{-1}$ significantly reduces the number of diluted eclipsing binaries if compared for example to the ~14"pixel$^{-1}$ of the HATNet and WASP surveys. However, it is still expected that 80 – 90% of the HATSouth candidates will end up being false positives. An important fraction (~ 40%) of HATSouth candidates have bright and moderately bright stars ($V < 14$). These objects can be targets of
photometric and spectroscopic follow-up campaigns carried out from the ground to confirm their planetary nature.

1.3.2 Current status

Regular operations of HATSouth started on 2011 after ~1 year of shakedown period. Since then, HATSouth has collected 2.9 million science images of 9.5 million stars with $r < 16$ at 2% per-point precision. From these data, 1412 objects have been selected as TEP candidates and ~ 400 of them have been already rejected as false positives, while the planetary nature of another ~ 50 candidates have been confirmed.

1.4 Thesis Outline

In this dissertation I will describe the work that I have performed during the past ~4 years related to the spectroscopic follow-up observations of TEP candidates discovered by the HATSouth survey. My specific work comprised the composition of the proposals to the telescope allocation committees, the planning and execution of the observations, the processing and analysis of the data and the final publication of some of the confirmed TEPs with detailed scientific analysis included. However, most of my efforts were concentrated in the third step, which consisted in the development of new computational tools for handling spectroscopic data. These tools were used in all of the HATSouth discoveries and were used also to reject an important fraction of the false positives. In Chapter 2, I describe the tools and algorithms that were developed for processing the raw data obtained with different instruments in an automated and homogeneous way. In Chapter 3, I present the code ZASPE, which is an algorithm to estimate stellar atmospheric parameters with their complete covariance matrix from high resolution echelle spectra.
In Chapters 4 and 5, the discoveries of three TEPs (HATS-9b, HATS-10b and HATS-17b) are reported; those publications were led by me. Finally, in Chapter 6, I present a brief summary of the thesis and I show how the new discoveries of HATSouth, in which I have been an important player, are truly expanding the parameter space of TEPs amenable for detailed characterisation.
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Chapter 2

CERES: The Complete ECHELLE REduction System

Abstract

CERES is a set of tools for the reduction and analysis of echelle spectra. The main purpose of CERES is the construction of fully automated, homogeneous and robust pipelines for processing data originating from different echelle spectrographs. Currently, CERES has been used to build pipelines for 10 instruments that have a wide diversity of properties. The principal goal of these pipelines is to obtain optimal quality spectra for computing precise radial velocity
measurements and to estimate stellar atmospheric parameters.

2.1 Introduction

Radial velocity variations produced by stellar mass companions have semi-amplitudes of $K \geq 5$ km s$^{-1}$ and can be easily measured with common low resolution spectrographs by identifying Doppler shifts of individual strong absorption lines. However, in the case of planetary mass companions around Sun-like stars, the resulting semi-amplitudes range from $K \approx 100$ m s$^{-1}$ for Jovian planets in short period ($a < 0.1$ AU) orbits to $K \approx 0.1$ m s$^{-1}$ for earth-mass planets in earth-like orbits ($a \approx 1$ AU). In order to achieve the required RV precision for detecting such subtle RV variations, high-resolution spectrographs have to be used. The resolving power ($R = \lambda/\Delta \lambda$) of these instruments can range from $R = 50,000$ to $R = 150,000$. In addition, they need to have a wide spectral coverage in order to include as many narrow absorption lines ($N_i$) as possible for increasing the RV precision ($\sigma_{RV} \propto N_i^{-1}$). Echelle spectrographs satisfy all these requirements by working at high incident angles on the diffraction grating producing high diffraction orders. In order to avoid the overlapping of continuous diffraction orders, a cross-disperser element is used which divides them, generating different echelle orders in a rectangular format that are then registered by a CCD. Figure 2.1 shows a typical raw image obtained with an echelle spectrograph where the normal dispersion goes horizontally and the cross-dispersion goes in the vertical direction. In general, echelle spectrographs have of the order of 50 orders covering the complete optical wavelength range, but new instruments are being designed to work in the infrared range as well.

Echelle spectrographs must be stabilised in order to measure the slight RV variations of stars produced by orbiting planets. Several of them are located in closed rooms where temperature and pressure conditions are controlled and they are fibre fed with the stellar light. However,
Figure 2.1: Raw image of the Coralie echelle spectrograph. The normal dispersion goes in the horizontal direction, while the cross-disperser divides the spectrum in 72 different orders distributed in the vertical direction, each one containing a different wavelength range. The curvature of each echelle order is also visible.
ambient conditions cannot be fully controlled and particular calibration techniques have been developed to trace subtle instrumental velocity shifts while the spectra are being acquired. The most typical are: (1) the simultaneous calibration lamp in which a second fibre is used to obtain the spectrum of a wavelength reference lamp containing numerous narrow emission lines; and (2) the absorption cell technique in which a cell of a molecular compound, typically iodine (12) in the optical, is located in the optical path of the light before entering the spectrograph, producing a forest of absorption lines superposed on the stellar spectrum that can be used to determine the instrumental drifts. Both techniques are able to deliver single measurement RV precision of $\sigma_{RV} \approx 1$ m/s.

In addition to the computation of precise RVs, echelle spectrographs have played a key role in the characterisation of stellar atmospheres. Given their high resolving powers, the narrow atomic absorption lines can be measured with great detail, while their wide spectral coverage allows to study all the chemical elements producing transitions in the stellar photospheres. The analysis of these absorption lines can be used to estimate the physical parameters of the star and also to study the distribution of the atomic abundances of stars in our galaxy.

However, one of the major drawbacks of echelle spectrographs is that the images registered by the CCDs contains several instrumental effects that have to be removed in order to fully take advantage of all the attributes that these instruments offer.

Photometric surveys of transiting extrasolar planets (TEPs), like HATSouth, extensively use echelle spectrographs for rejecting false positives, characterise stellar hosts and confirm true planets via the determination of their masses. Hundreds of stars with different physical properties, coordinates and magnitudes must be monitored with different echelle spectrographs during days, months and/or years, which translates in the acquisition of thousands of spectra per year that must be processed and analysed in the most efficient way in order to reach a significant
detection yield of TEPs. In order to achieve a long term RV precision, exactly the same reduction and calibration routines have to be applied to spectra acquired at different epochs; and also spectra of different targets obtained from different instruments should be processed and analysed homogeneously for reaching the best results. Moreover, the data must be processed as soon as possible in order to prioritize the future valuable observing time and thus the automatisation of the reduction processes is fundamental for saving human time that can be used into research. The absence of standardised reduction pipelines or in many cases the absence of any pipeline at all for some echelle spectrographs motivated the development of a robust framework for processing the follow-up data of HATSouth candidates. The development of our own reduction and analysis system give us also complete control over each step of the data processing which is highly beneficial for achieving the accuracy that we require. This framework, called CERES, is conformed of a set of tools that allow the construction of automatised, robust and homogeneous pipelines that take care of the reduction, extraction, calibration and analysis of echelle spectra originating from different instruments with almost no user intervention. CERES has been used to develop pipelines for ten instruments which have been fundamental in the confirmation of all HATSouth TEPs but have been also used in other projects with different science goals. In the following sections we describe in detail the tools that CERES uses for producing reduced spectra and derived results from raw echelle images.

2.2 General Structure

In general, all CERES pipelines have a main code that drives all the steps required to obtain a reduced and analysed spectrum. The main code can call functions from a general module (GLOBALutils.py) that contains tasks that can be used by different pipelines, but it can also call functions from another Python module that contains tasks specifically designed for a particular
instrument (utils.py). Most of the tools are coded in Python but there are also some time consuming functions that were written in C but which are wrapped to be called directly from Python. Some of the time consuming tasks have been also parallelized and the user can enter the number of cores to be used in the reduction. All pipelines follow mostly the same main structure, but there are several particular differences due to the differing properties of each instrument. In this regard, there are two main categories of echelle spectrographs, namely the ones that are fibre fed from the telescope and the ones that use directly a slit. Commonly the fibre-fed ones are much more stable and the structure of the associated pipeline is simpler.

2.3 Pre-processing

2.3.1 Classification of the image frames

The first step of any CERES pipeline is to identify all the images that are going to be used in the reduction process and to classify them according to their types. Given that there is no unified header keyboards, we use a particular function for each spectrograph that performs the classification. Common image types are: bias frames, dark frames, flat frames, wavelength calibration frames and science images.

2.3.2 Master CCD Frames

Once the classification of the images is done, the next step is to construct the master CCD calibration images by median combination. The only master calibration image type that is commonly used by all instruments are bias frames. Dark frames are only used by the DuPont and PUCHEROS spectrographs, where the pipeline computes a master dark frame for different
exposure times.

Image flat frames are generally only used in some of the slit echelle spectrographs, because in order for a flat frame to be useful it must illuminate smoothly the complete CCD but at the same time it must contain the approximate wavelength dependence that each pixel has due to the dispersed light. In the case of the DuPont telescope for example, this kind of images are produced by using a diffuser after the light of the afternoon sky has been dispersed by the spectrograph. This mechanism allows to illuminate the inter and intra order regions of the CCD while saving the response of the particular pixels to the approximate corresponding wavelength. This images (milky flats) are median combined and then, in order to obtain only the pixel-to-pixel variation, this master image is divided by a median-filtered version of the same image. These master flat CCD frames can be used then to correct the pixel-to-pixel variations of the science frames. Some other slit echelle spectrographs like MIKE and PFS use wide slit flats, where in this case spectra of a continuum lamp is acquired, but using a wider slit than the one used to acquire the science frames. These calibration images are median combined and the master image is also divided by its median combined version. In the case of fibre-fed spectrographs the correction of pixel-to-pixel variations is not possible and another approach is used, as explained in section 2.6.

2.3.3 Identification of the echelle orders

One key step in the processing of echelle data is the identification and tracing of the echelle orders. In the case of fibre-fed spectrographs, an image of the spectra of a continuum lamp is used to perform this procedure, while a spectrum of a bright object is used for slit spectrographs. In order to find the orders, the central columns of the image are used because usually they have higher SNR than the other zones. The exact number of columns is a free parameter that can
be modified by the user but usually is of the order of 10 pixels. These columns are median combined in the simple dispersion direction for constructing a reference vertical cut of the CCD without cosmic rays or cosmetic artefacts. Then, this reference column is convolved with a Gaussian kernel for smoothing it, where the width of the Gaussian is another parameter that can be modified by the user. All the peaks of the smoothed reference column are identified and then an iterative procedure is applied to reject shallow peaks that have smaller counts than $N$ times the dispersion of the counts in the inter-order zones, where $N$ is another adjustable parameter. Figure 2.2 shows the vertical cut in an image obtained with the echelle spectrograph mounted on the DuPont telescope that is used to identify the orders.

As opposed to common spectrographs, the traces of echelle spectrographs have a strong curvature. Starting from the central position of each order computed in the last step, the vertical position of the order in each column is identified by fitting Gaussian functions in zones centred on the position of the already identified contiguous column, where the width of the zone must be similar to the approximate vertical extension of the orders. In order to avoid errors in the traces arising from low SNR, cosmic rays, or instrumental artifacts in some orders, a procedure is applied in which the drift of the orders between the new column and the previous column is computed and the orders that show drifts 3 times greater than the dispersion are rejected and the centroid for those orders is replaced by the one of the contiguous order plus the median drift.

Finally a high order polynomial is fitted to the centroids of each order and the coefficients of the fit are saved for extracting the science and calibration spectra. Figure 2.3 shows a portion of a DuPont image and the traces identified by the CERES algorithm.

Some slit spectrographs mounted directly on the telescope can suffer from strong flexures, which produces that the traces can significantly change depending on the pointing position of the telescope. To handle this effect, CERES includes a function to retrace the orders by using
Figure 2.2: Vertical cut of an echelle image used to identify the echelle orders. Some peaks that the algorithm select as maxima are then iteratively rejected (red points) while the remaining ones are selected as the true orders (blue points).

the reference traces and performing a cross-correlation against the science images in the pixel scale. The pixel displacement of the maximum of the cross-correlation function is determined as the instrumental drift and all the reference traces are displaced by that amount.
Figure 2.3: A portion of an image obtained with the echelle of the DuPont telescope. The black solid lines correspond to the traces of the echelle orders identified by the CERES algorithm. It can be seen that the algorithm has a good performance in zones with low SNR and also in areas that have instrumental artefacts.

2.3.4 Scattered light subtraction

In echelle spectrographs, in addition to the dispersed light registered in each order, some scattered light is also detected by the CCD which is generated by the echelle grating and the roughness of the optical surfaces. This contamination produces a smooth background that has to be removed before extracting the spectra in order to conserve the true depth of the absorption lines.
CERES uses a simple algorithm to correct for this effect. At this step, the traces of the orders and their width are already known which can be used to select only the inter order zones of the image. For each column, the algorithm computes the median flux in each inter order region and then a linear interpolation of these values in the vertical direction is performed to infer the scattered light level in the intra-order regions of the image. Finally, a two dimensional median filter is applied to the constructed scattered light surface to smooth the effects of spurious signals and the filtered image is subtracted from the original science image.

2.4 Extraction

The extraction of a spectrum refers to the process of adding up all the signal of the trace in the direction perpendicular to the dispersion, going from a 2D image to a 1D spectrum. In the case of an echelle spectrograph the extraction process produces a 1D spectrum for each order. Before adding up the signal, all the systematic effects must be removed, which means that the master calibration frames must be applied to the science image, bad columns must be corrected and the scattered light background must be subtracted. All these previous steps are carried out by CERES. CERES contains two algorithms for performing the extraction. The most simple one corresponds to the simple sum of the flux of all the pixels contained in a vertical window of width defined by the user. This algorithm is known as simple extraction. The second algorithm that CERES contains is called optimal extraction, which is particularly useful to obtain high quality spectra from low SNR distorted data and is based on the work of Marsh (1989). This algorithm relies on the determination of the appropriate weights across the profile of the objects that produce the minimum variance for the expected value of the total flux. For computing these weights, the fraction of the flux of the object which falls in each pixel is determined by fitting polynomials in the dispersion direction to the normalised profiles. The number of polynomials
must be higher than the width in pixels of the order and can be modified by the user. The polynomials are computed in an iterative process which allows to identify cosmic rays and correct for them. In the case of stable fibre-fed spectrographs, the weights are computed from a calibration image known as fibre flat, which corresponds to a spectrum of a continuum lamp. In the case of slit spectrographs, the weights are computed from the same science images that are being extracted.

## 2.5 Wavelength Calibration

### 2.5.1 ThAr lamps

The most common procedure for calibrating the science spectra in wavelength is to use the spectrum of a reference lamp filled with a particular gas. When this gas is heated it radiates only in certain narrow emission lines according to the particular allowed electronic transitions of the atoms present in the gas. If the lamp has been characterized, it can be used to generate a mapping between the pixel position and the corresponding wavelength. In the case of echelle spectrographs the most commonly used calibration lamp is one composed of thorium (Th) and argon (Ar). The reason for this choice lies in the wide wavelength coverage of the transitions of both elements. On one side the emission spectrum of Th is densely populated for wavelengths shorter than 6000 Å, while the Ar lines are visible even at $\lambda = 10000$ Å, but being less numerous. The reference wavelength solution of a given night is usually obtained with the calibrations taken in the afternoon and posterior ThAr spectra are obtained during the night to trace the instrumental drift of the system. In the case of unstabilised instruments like the ones mounted on the telescope or the ones that are not controlled in temperature and pressure, additional ThAr exposures must be obtained before and after each science image in order to reach the
best RV precision achievable. For stabilised instruments like HARPS, Coralie and FEROS the acquisition of ThAr spectra during the night may be not mandatory. However in the case of these instruments a second fibre is always available for obtaining a simultaneous ThAr spectrum while observing the science target to trace subtle instrumental drifts.

Once the spectra of the ThAr lamp have been extracted the process to compute the wavelength solution is the same for every spectrograph. However, for each echelle order the pipeline requires to have a reference text file with the exact wavelength value and approximate pixel position of each emission line to be used in the calibration. First a rough cross-correlation function (CCF) in the pixel domain is performed between the flux of each echelle order containing the spectrum of a lamp and a binary mask generated from the text file with ones in the positions of the emission lines and zeros elsewhere. The position of the maximum of this CCF is used to trace any long term instrumental drift. After correcting by this drift, Gaussian functions are fitted to the ThAr flux in zones around the approximate pixel position of the emission lines. The mean of each Gaussian is used as the exact pixel position of the emission lines. After this procedure each emission line possesses a wavelength value \( \lambda_i \), a precise pixel position \( x_i \) and an echelle order \( j_i \), which extends from 0 to the number of detected orders minus 1, ordered from the reddest to the bluest.

The next step consists in fitting iteratively a polynomial between \( \{ p_i \} \) and \( \{ \lambda_i \} \) for each echelle order \( j \), in order to reject strong outliers that correspond to poorly identified emission lines. This procedure delivers also the approximate wavelength value of the central pixel of each echelle order \( j_i \) \( (\lambda^*_j) \), which can be used to determine the real order numbers \( \{ m_j \} \) of the instrument. In practise, we search for the integer \( m_0 \) such that

\[
m_0 + j = m_j. \tag{2.1}
\]
The grating equation states that $\lambda \propto m^{-1}$ and therefore the correct $m_0$ value will be the one that produces the smaller slope of the following equation:

$$y(j) = (m_0 + j)\lambda_j^*.$$  \hspace{1cm} (2.2)

Once $m_0$ has been determined, each emission line will have also its corresponding *real* echelle order $m_i = j_i + m_0$.

After rejecting the strong outliers and determining the *real* order numbers, the pipeline computes a global wavelength solution in the form of an expansion of the grating equation (see Section 2.6 in Baranne et al. 1996) using Chebyshev polynomials, and more lines are iteratively rejected until the *rms* of the global solution is below a certain threshold that depends on the instrumental resolving power$^1$. Our global wavelength solution takes the form

$$\lambda(x, m) = \frac{1}{m} \sum_{i=0}^{n_m} \sum_{j=0}^{n_x} a_{ij} c^i(m)c^j(x),$$ \hspace{1cm} (2.3)

where $x$ and $m$ refer to the pixel value and echelle order number, respectively, $c^n$ denotes the Chebyshev polynomial of order $n$, $a_{ij}$ are the coefficients that are fitted to obtain the wavelength solution, $n_m$ is the degree of the Chebyshev polynomial in $m$ and $n_x$ is the degree of the Chebyshev polynomial in $x$. The values of $n_m$ and $n_x$ will depend on the particular properties of each instrument. Figure 2.4 shows an example of the global wavelength solution of the FEROS spectrograph that produced the best fit. The bottom panel of that figure shows that the residuals in the wavelength position of the ThAr emission lines are in general below 0.003 Å.

For computing the drifts in wavelength of the ThAr lamps that are acquired during the night, the pipeline repeats the process described in the previous paragraph but in this case we hold fixed the $a_{ij}$ coefficients found in the reference ThAr lamp of the afternoon and we fit only for

$^1$Formally, the threshold we use is $3\lambda_{\lambda_{3969}}$ Å.
Figure 2.4: Top panel: global wavelength solution that produces the best fit to the positions of the emission lines of a ThAr lamp observed with the FEROS spectrograph. The points correspond to the wavelength of the particular emission lines that are used in the fit and are coloured differently for each echelle order. The solid line is the fitted global solution. Bottom panel: residuals produced with the global wavelength solution of the top panel.
the $\delta v_{\text{inst}}$ velocity shift using the following model:

$$
\lambda(x, m) = \frac{1}{m} \left( 1 + \frac{\delta v_{\text{inst}}}{c} \right) \sum_{i=0}^{n_x} \sum_{j=0}^{n_x} a_{ij} e^i(m) e^j(x). 
$$

(2.4)

2.5.2 Fabry-Perot system

Even though the use of ThAr lamps allows to achieve very precise wavelength solutions that enable the computation of precise RVs, they are quite far from being perfect calibrators. Only few emission lines are generally visible in the bluer ($\lambda < 4000$ Å) and redder ($\lambda > 7000$ Å) parts of the wavelength coverage. The intensities of the lines are not uniform, which produces the saturation of some lines in some orders in order to allow the detection of fainter ones. In some cases when the simultaneous calibration lamp is used, the saturation of some ThAr lines can even contaminate contiguous orders dedicated to obtain the science spectra. Moreover, the internal composition of the lamps can change, which can produce long term instrumental drifts in the measured RVs. Also, they do expire at some point and some subtle manufacturing differences in the lamps can induce other systematic errors if a new lamp is installed. A couple of alternative wavelength calibration systems have been developed with the goal of replacing the use of the ThAr lamps. The most promising one is the laser frequency comb (Li et al. 2008), which produces a forest of emission lines with similar intensities whose exact wavelength positions can be synchronized with radio-frequency oscillators referenced to atomic clocks. However, the cost of such systems is rather high and they are still under study and development. An alternative approach is the use of Fabry-Perot interferometers, in which a pair of parallel reflecting surfaces that are illuminated with a continuum source produce a fringed pattern due to the constructive and destructive interference that arises from the interaction of the light reflected in both surfaces. The spectra produced by a Fabry-Perot system is populated with a forest of emis-
sion lines that extend across the full wavelength coverage of the spectrograph and where the separation between two contiguous lines depends on the effective distance of the two reflective plates. With this type of systems, the long term precision of the wavelength calibration does not depend on the source lamp and only on the properties of the reflective plates. Figure 2.5 compares two spectra in an echelle order, one obtained with a ThAr lamp and the other obtained with a Fabry-Perot system.

One of the major drawbacks of Fabry-Perot interferometers as wavelength calibration systems is that they do not deliver directly an absolute wavelength calibration as opposed to ThAr lamps where the characteristic pattern of the spectrum can be used to associate specific wavelengths to each line. What is commonly done in spectrographs like Coralie is to compute the absolute wavelength calibration with the spectrum of a ThAr lamp obtained in the afternoon calibrations. Immediately after that, the absolute solution is then improved with the acquisition of Fabry-Perot spectra. The instrumental drifts during the night are calculated then by the acquisition of Fabry-Perot spectra with the comparison fibre. With this procedure the ThAr lamp is only marginally used, extending its useful life, the wavelength solution is determined with higher accuracy and the science observations do not suffer from the contamination of saturated ThAr lines.

CERES includes the functions required for handling Fabry-Perot spectra and they have been added to the pipeline that handles data from the Coralie spectrograph. In this case, for computing the wavelength calibration of a science spectrum, 3 images are required: the ThAr lamp at both fibres (TH2), the ThAr lamp at the object fibre while the Fabry-Perot is at the comparison fibre (THFP); and the stellar spectra at the object fibre while the Fabry-Perot is at the comparison fibre (OBFP). The global absolute wavelength solution is computed for both fibres with the reduced spectra of TH2. Then, the Fabry-Perot spectra of the comparison fibre in THFP is
Figure 2.5: Top: extracted spectrum of a ThAr lamp for one order of the Coralie spectrograph. It shows the presence of emission lines with different intensities that are non-uniformly distributed. Bottom: extracted spectrum of a Fabry-Perot system for the same order and spectrograph of the top panel. In this case the spectrum is densely populated with emission lines which have similar intensities.
calibrated in wavelength by the computation of $\delta \nu_{inst}^1$ between the ThAr spectra of the TH2 and THFP images using equation 2.4. Finally the instrumental drift $\delta \nu_{inst}^2$ between the THFP and the OBFP images is calculated via the computation of the cross-correlation function between both Fabry-Perot spectra.

2.6 Final output and post-processing

Several outputs are produced after each pipeline is executed. The reduced spectrum is found in a three dimensional fits file with the following general form: [data type, echelle order, pixel]. The data type dimension has generally eight entries. The first entry ([0, :, :]) is the matrix containing the wavelengths of each pixel for each echelle order after computing all the instrumental velocity drifts. The second entry ([1, :, :]) corresponds to the optimally extracted stellar flux. The top panel of Figure 2.6 shows the extracted flux of a G-type star for one order obtained with the FEROS spectrograph. The third entry contains a measure of the noise (inverse variance) associated to each order obtained from the optimal extraction procedure. The fourth column corresponds to the deblazed stellar flux (central panel of Figure 2.6) and the fifth column contains its associated inverse variance. In echelle spectrographs, the flux of each order registered by the CCD contains a strong instrumental modulation which has to be corrected in order to be analysed. This instrumental effect is known as the blaze function. In the case of fibre fed spectrographs the blaze is partially corrected by dividing the extracted spectra by the spectrum of a continuum lamp (fibre flats) which also partially corrects the pixel-to-pixel variations. For echelle spectrographs using slits, this effect can be partially corrected by using the spectrum of a hot and rapidly rotating star where a high order polynomial or some particular function is fitted to each echelle order. However in both cases, given the differences in the continuum emissions of the observed star and the blaze correcting object, the deblazed
spectra will end up having a particular slope or smooth variation that will not reflect the shape of the continuum of the observed star. The recovery of the stellar continuum can be only found if the spectral energy distribution of the calibrator is accurately known. However, echelle spectrographs are generally used for studying the absorption lines and not the continuum. For this reason the sixth and seventh entries of the output correspond to the continuum normalized flux and its associated inverse variance, respectively (bottom panel of Figure 2.6). The continuum normalisation is obtained by fitting a low order polynomial to the deblazed flux including an iterative procedure that excludes absorption lines from the fit. Finally the eighth column corresponds to the SNR per pixel in the continuum of the observed spectrum. In addition to the reduced and wavelength calibrated spectra CERES contains several functions that are used by the pipelines to analyse the spectra in an homogeneous way, as we now detail.

2.6.1 Radial Velocities

The information about the velocity of the observed star is contained in the wavelength position of its spectral lines. Griffin (1967) showed that a very efficient way for using simultaneously the information provided by all the observed lines for measuring precise radial velocities is to use the cross-correlation function (CCF), which can be used even with low SNR data. Following this idea, CERES includes a set of functions for the computation of the CCF using a binary mask (Baranne et al. 1996). The mask takes values equal to 1 in the regions where a typical stellar spectra contains narrow absorption lines and equal to 0 elsewhere. The exact regions of the mask associated with absorption lines will depend on the atmospheric properties of the star (principally on $T_{\text{eff}}$). For this reason there are 3 available masks for 3 different spectral types (G2, K5 and M5) that can be used to compute the RV of the observed spectrum. These masks are the same ones used by the data reduction system of HARPS (Mayor et al. 2003). The
Figure 2.6: The top panel shows the extracted flux of a solar type star in one echelle order of the FEROS spectrograph. The middle panel shows the same spectrum divided by the corresponding spectrum of the fibre flat, while the bottom panel shows the continuum normalised spectrum.
default mask for all the pipelines is the G2 but it can be changed by the user if the properties of the observed star are known and are closer to the ones of the other masks. However, a key point here is analysing all the spectra of a particular star with the same mask, because the use of different masks will produce different zero point velocities that can be responsible of increasing the dispersion of the radial velocity measurements, hindering the detection of a Keplerian variation.

The algorithm that computes the CCF includes the effects of pixelization and computes one CCF for each echelle order before combining them using a weighted sum according to the median SNR of each order. The CCF for the echelle order \( m \) at a certain velocity \( v \) can be expressed as

\[
CCF^m(v) = \frac{\int_{\lambda_i}^{\lambda_f} W(\lambda') F(\lambda) M(\lambda') d\lambda}{\sqrt{\int_{\lambda_i}^{\lambda_f} M(\lambda')^2}},
\]

(2.5)

where \( \lambda_i \) and \( \lambda_f \) are the wavelengths of the initial and final pixels of the order \( m \), \( F(\lambda) \) corresponds to the observed spectrum, \( W(\lambda') \) corresponds to the weight that each spectral zone has according to the binary mask and \( M(\lambda') \) is the binary mask shifted to the \( \lambda' = \lambda(1 + v/c) \) wavelength positions due to the Doppler displacement, where \( c \) is the speed of light. As defined in equation 2.5, the CCF will acquire its minimum values for \( v \) close to the radial velocity of the observed star. The actual RV is computed by fitting a Gaussian to the CCF, and the resulting mean is taken to be the RV of the star. Figure 2.7 shows an example of a CCF computed from a FEROS spectrum and its corresponding fitted Gaussian.

During nights with a bright Moon, the spectrum of the Sun reflected by the moon can strongly contaminate the spectrum of the target star producing an additional peak in the CCF that can systematically alter the measured RV of the star. CERES also includes tools for determining the impact that moonlight contamination produces on the RVs. Using the pyephem package
Figure 2.7: CCF computed from a FEROS spectrum of a single G-type star. The blue points correspond to the computed CCF while the red line is the best Gaussian fit.
we compute the coordinates that the moon possesses at the time of the observations and we also estimate the RV at which the solar spectrum should show up in the CCF. In addition, from previous simulations we also know the width of the CCF peak produced by this contaminant. If the Moon is above the horizon and produces an important peak in the CCF close to the one produced by the star, then we simultaneously fit two Gaussians to the computed CCF, where the Gaussian corresponding to reflected sunlight has only one free parameter, namely the depth of the peak produced by the moonlight contamination. Figure 2.8 shows a CCF that is heavily contaminated and the corresponding best fit of Gaussians.

Uncertainties on the RVs are determined from the width of the CCF and the mean SNR close to the Mg triplet zone using empirical scaling relations (as in Queloz 1995) whose parameters are determined using Monte Carlo simulations where Gaussian noise is artificially added to high S/N spectra. The exact equation used to estimate the RV error is

$$\sigma_{RV} = b + \frac{a(1.6 + 0.2\sigma_{ecf})}{SN_{5130}},$$

(2.6)

where $a$ and $b$ are the coefficients obtained via the Monte Carlo simulations and depend on the applied mask, $SN_{5130}$ is the continuum SNR at 5130 Å and $\sigma_{ecf}$ is the dispersion of the Gaussian fit to the CCF. For illustration, the values of the coefficients for the G2 mask in the case of the Coralie spectrograph are $a = 0.06544$ and $b = 0.00146$ (in km s$^{-1}$).

In order to measure the absolute RV variations in a star produced by a planetary companion it is required to correct the RV of the observed spectra for the velocity that the observer has with respect to the star. This procedure is known as the barycentric correction and consists in computing the velocity that the observatory has with respect to the barycentre of the solar system projected in the direction of the observed star. The two principal velocities that have to be computed are the movement of the earth around the barycentre and the rotation of the
Figure 2.8: CCF computed from a FEROS spectrum of a single star that is strongly contaminated by the scattered moonlight. The red line corresponds to the fit to the CCF performed with a single Gaussian. The black dashed line corresponds to the inferred RV of the spectrum of the moon, while the green line corresponds to the best fit of the two Gaussian model which allows to recover the RV precision for the targeted star.
earth at the geographical coordinates of the observatory. In order to determine the barycentric correction CERES uses the Jet Propulsion Laboratory ephemerides (JPLephem) package which is written mostly in C and fortran but can be called directly from Python.

2.6.2 Bisector Spans

Another useful parameter that can be extracted from the CCF is the bisector span (BS) which is a measure of the asymmetry of the absorption lines. The absorption lines can be naturally asymmetric due to the convective motions in the surface of the star (macro turbulence), where the luminosity of the raising material is greater than the one of the material that is entering back the interior of the star. The observed spectrum corresponds to the disk integrated stellar intensity and the effect of the different intensities in the rising and receding material leads to the formation of asymmetric absorption lines. However, if the star has low levels of activity, the degree of asymmetry produced by convection is constant in time. Variations in the measured bisector spans can lead to variations in the measured RVs that can be associated with false positive scenarios. For example, eclipsing binary systems in which both peaks cannot be resolved in the CCF will produce this kind of behaviour in the single CCF peak. Similarly, stellar activity leads to time correlated BSs variations. In order to confirm the planetary nature of a TEP candidate, RV and BS variations must be uncorrelated. CERES computes the BS from the CCF following Queloz et al. (2001). The bisector is computed as the mean velocity $B(d)$ at the depth $d$ between both sides of the CCF peak as

$$B(d) = \frac{v_l(d) + v_r(d)}{2},$$

where, based on Figure 2.9, $v_l$ correspond to the velocities located on the left side from the minimum of the CCF peak and $v_r$ are the ones on the right side. Then, the mean bisector is
Figure 2.9: Left: The blue points correspond to the computed CCF while the green line traces all the bisector measurements at different depths. Right: Zoom-in of the bisectors shown in the left panel. The coloured regions correspond to the two zones where the median bisectors are computed.

computed at two depths ranges: from $d = 0.1$ to $d = 0.4$ and from $d = 0.6$ to $d = 0.85$ obtaining

$$\bar{B}_{0.1-0.4} = E[B(d)], \forall 0.1 < d < 0.4,$$ \hspace{1cm} (2.8)

$$\bar{B}_{0.6-0.85} = E[B(d)], \forall 0.6 < d < 0.85.$$ \hspace{1cm} (2.9)

Finally, the BS value is obtained from the difference of both quantities as

$$BS = \bar{B}_{0.1-0.4} - \bar{B}_{0.6-0.85}.$$ \hspace{1cm} (2.10)

Figure 2.9 shows the parameters that are extracted from the CCF for computing the bisector span.

The errors in the BS measurements are estimated using a scaling relation that depends on the
SNR in the region of the Mg triplet only as

\[ \sigma_{BS} = \frac{a}{SN_{5130}} + b, \]  

(2.11)

where \( a \) and \( b \) are coefficients determined from Monte Carlo simulations, with random noise added to high SNR spectra for different spectral types.

### 2.6.3 Rough stellar classification

CERES also includes a tool for a fast estimation of stellar atmospheric parameters of the observed spectra. In order to estimate the stellar parameters \( (T_{\text{eff}}, \log(g), [\text{Fe/H}], v_{\text{sin}i}) \) we cross-correlate the observed spectrum against a grid of synthetic spectra of late-type stars from Coelho et al. (2005) convolved to the resolution of the spectrograph and a set of \( v_{\text{sin}i} \) values given by 0, 2.5, 5, 7.5, 10, 15, ..., 45, 50 km s\(^{-1}\). First, a set of atmospheric parameters is determined as a starting point by ignoring any rotation and searching for the model that produces the highest cross-correlation using only the Mg triplet region. We use a coarse grid of models for this initial step (\( \Delta T_{\text{eff}} = 1000 \, \text{K}, \Delta \log(g) = 1.0, \Delta [\text{Fe/H}] = 1.0 \)). A new cross-correlation function (CCF) between the observed spectrum and the model with the starting point parameters is then computed using a wider spectral region (4800 – 6200 Å). From this CCF we estimate RV and \( v_{\text{sin}i} \) values using the peak position and width of the CCF, respectively. New \( T_{\text{eff}}, \log(g), \) and \([\text{Fe/H}])\) values are then estimated by fixing \( v_{\text{sin}i} \) to the closest value present in our grid and searching for the set of parameters that gives the highest cross-correlation, and the new CCF is used to estimate new values of RV and \( v_{\text{sin}i} \). This procedure is continued until convergence on stellar parameters is reached. For high SNR spectra, uncertainties of this procedure are typically 200 K in \( T_{\text{eff}}, 0.3 \) dex in \( \log(g), 0.2 \) dex in \([\text{Fe/H}], \) and 2 \( \text{km s}^{-1} \) in \( v_{\text{sin}i} \). These uncertainties were estimated from observations of stars with known stellar parameters from the
literature. Results of our stellar parameter estimation procedure are obtained in about 2 minutes using a standard laptop. Fast and robust atmospheric parameters are estimated in order to make efficient use of the available observing time because in this way some false positives or troublesome systems, such as fast rotators and giants, can be identified on the fly during the follow-up process.

2.7 Supported Instruments

Currently, CERES has been used to build fully automated reduction and analysis pipelines for 10 echelle spectrographs. I will describe now some specifications about each pipeline.

- Coralie: This is a R=60,000 echelle spectrograph installed at the 1.2m Euler/Swiss telescope at La Silla Observatory. It is fibre fed from the telescope to a 2Kx2K CCD and includes also a second fibre that can be used to acquire a simultaneous spectrum of the sky or of a wavelength comparison source (ThAr lamp or Fabry-Perot system). It is placed in a fully controlled room where the temperature and vibrational conditions are stabilised. This instrument was the initial motivation for developing CERES. The current CERES pipeline is able to handle the ThAr and Fabry-Perot simultaneous calibration modes delivering a long term RV precision of $\sigma_{RV} \approx 8 \text{ m s}^{-1}$ based on observations of stars whose RVs have been reported to be constant at the 1 m s$^{-1}$ level (see Figure 2.10).

- FEROS: The Fibre-fed Extended Range Optical Spectrograph is installed at the 2.2m MPG telescope in La Silla Observatory and delivers a spectral resolution of R=50,000 by using an image slicer. It has 39 orders which are registered by a 4Kx2K CCD and contains also a comparison fibre that can be used to obtain a simultaneous spectrum of the sky or a simultaneous ThAr lamp. It is placed in a separate room where the environmental
Figure 2.10: RV measurements for two RV standard stars observed with Coralie and processed with the CERES pipeline. The top panel is for the G9V type star HD72673 and the bottom panel is for the G3V type star HD157347. In both cases, the \textit{rms} is around 8 m/s.

conditions are monitored and stabilised. The development of a pipeline for the FEROS spectrograph was primarily motivated by the fact that the official pipeline was not built to deliver precise RV measurements and was also unable to deliver good quality spectra for low SNR data. Due to some technical peculiarities of this instrument, several algorithms of our FEROS pipeline were specifically designed for it because the general one cannot be directly applied. Our FEROS pipeline has its own function for the determination of the traces because the image slicer causes that vertical profile of each order to show a double peaked shape as opposed to the Gaussian shape of typical fibre fed spectrographs (see Figure 2.11). The algorithm is similar, but in this case the centroid of the profile used to detect the orders is found by fitting two Gaussians and computing the average of their means. Another important difference is that we do not process all the echelle orders because the precision of the wavelength solution significantly worsens if all of them are
included in the fit. Therefore our final FEROS output has 25 echelle orders covering from 3800 Å to 6800 Å. Our pipeline is able to process data with the simultaneous ThAr lamp achieving an RV precision of $\sigma_{RV} \approx 5 \text{ m s}^{-1}$ on bright targets as opposed to the $\sigma_{RV} > 30 \text{ m s}^{-1}$ obtained with the official pipeline.

![Graph](image.png)

Figure 2.11: The green line corresponds to the typical profile of a fibre-fed echelle spectrograph, while the blue line shows the profile of the FEROS spectrograph, where the two peaks are produced by the image slicer that this instrument uses to achieve a resolution of R=50,000.

- HARPS: The High Accuracy Radial velocity Planet Searcher is an echelle spectrograph installed at the 3.6m telescope in La Silla Observatory. It is one of the most ambient-stabilised fibre fed spectrographs in the world and is capable of detecting planets a few times more massive than the Earth. Its spectral resolution is R=120,000 and it possesses 72 echelle orders which are registered by a 2 chip mosaic detector of total size 4Kx4K. It is housed in a vacuum vessel to avoid spectral drifts due to temperature and air pressure variations which produce instrumental variations $< 1 \text{ m s}^{-1}$ along the night. It also possesses a second fibre that can be used to monitor the background sky or to obtain a simultaneous wavelength calibration. Our pipeline for HARPS was developed just for completeness in order to process HATSouth data with the same algorithms that we apply on our FEROS and Coralie data. This pipeline achieves a $\sigma_{RV} \approx 2 \text{ m s}^{-1}$, slightly higher
than the $\sigma_{RV} \approx 1$ m s$^{-1}$ of the official data reduction software.

- CAFE: The Calar Alto Fiber-fed Echelle spectrograph is installed in the 2.2m telescope at the Calar Alto Observatory in Spain. It is placed in a temperature and vibration controlled room but it does not count with a simultaneous calibration system. The resolution of this instrument is $R=70,000$ and the complete optical spectrum is divided in 84 orders and registered in a 2Kx2K CCD. I was asked to develop a pipeline for this instrument for performing the follow-up of Kepler planetary candidates. Due to the absence of a comparison fibre, the RV precision of the CERES pipeline for this instrument is $\sigma_{RV} \approx 30$ m s$^{-1}$ which is enough to confirm the planetary nature of massive candidates.

- PUCHEROS: This instrument is a R=20,000 fibre fed echelle spectrograph built by the Centro de Astroingenieria at PUC/Chile and installed at the 0.5m telescope of the Observatorio UC near Santiago. The achievable RV precision is $\sigma_{RV} \approx 100$ m s$^{-1}$ because it is not placed in a controlled room and does not count with a simultaneous wavelength calibration system. The CERES pipeline is the official reduction system for this instrument and is installed at the observatory. The small aperture of the telescope translates in that most of the observations have low SNR for which the optimal extraction of the CERES pipeline plays a fundamental role in delivering good quality data.

- DuPont: This instrument is an echelle spectrograph mounted on the 2.5m DuPont telescope in Las Campanas Observatory. Currently, the CERES pipeline is only able to process data acquired with the 1” slit which delivers a resolution of R=40,000. This spectrograph is very unstable and the flexures of the telescope produce that the vertical and horizontal positions of the orders change with the position of the telescope. However the pipeline is able to retrace the orders and deal with these stability related issues. The RV precision of the pipeline is $\sigma_{RV} \approx 200$ m s$^{-1}$. The development of a pipeline for this
instrument was motivated by the absence of an official pipeline and because we used it for performing reconnaissance spectroscopy of HATSouth candidates.

- MIKE: The Magellan Inamori Kyocera Echelle spectrograph is mounted on the 6.5m Clay telescope at Las Campanas Observatory. The spectra is separated into two arms and both portions are registered in different CCDs. The development of this pipeline was just for completeness because the final goal of CERES is to be able to process data from at least every echelle spectrograph installed in Chile. Currently the CERES pipeline can only process the red arm (4900 Å-9500 Å) with the 1” slit that delivers a resolution of R=65000. This instrument is also mounted directly on the telescope which strongly affects the achievable RV precision. The actual RV precision is unknown due to the lack of enough observations of RV standard stars.

- PFS: The Carnegie Planet Finder Spectrograph is also mounted on the Clay telescope but this instrument uses the I2 cell technique for achieving precise RV measurements. The official pipeline developed and managed by the PFS team delivers an RV precision of $\sigma_{RV} \approx 2 \, \text{m} \, \text{s}^{-1}$ for bright stars. The CERES pipeline does not handle data with I2 cell and for the moment it only relies on the wavelength calibration of a ThAr lamp. It was mainly developed for having the HATSouth spectra obtained with PFS in the same format as the spectra obtained with the other instruments for performing a spectral classification. We expect to develop modules to calibrate I2 cell spectra in the future.

- ARCES: The ARC Echelle Spectrograph is mounted on the 3.5m telescope at the Apache Point Observatory in New Mexico (USA), and has a spectral resolution of R=31,000. The CERES pipeline for this instrument was developed for analysing spectra of the host stars of TEP candidates from the HATNet survey.
Chapter 2. CERES

- HIRES: The High Resolution Echelle Spectrometer is mounted on Keck in Hawaii. We developed this pipeline for analysing spectra of some of the HATSouth candidates that are observed from this facility. The complete optical spectrum is registered in 3 CCD but currently, the CERES pipeline can only reduce data of the green chip (5000 Å-6000 Å).

2.8 Results

2.8.1 HATSouth results

The main motivation for developing CERES was for performing an homogeneous follow-up analysis of the HATSouth TEP candidates. In this regard, our set of echelle pipelines has been extremely useful. In four years of spectroscopic monitoring we have processed 1663 spectra of 269 candidates observed with FEROS, 644 spectra of 172 candidates observed with Coralie, 231 spectra of 121 candidates observed with the DuPont telescope and 471 spectra of 111 candidates observed with HARPS. For all of them we obtained precise RV, BS measurements and a rough estimation of the stellar parameters using CERES, usually as soon as the data was acquired, which allowed us to adjust the observing priorities of the candidates on the fly and make an efficient use of our observing time. All these spectra have been fundamental for rejecting a large fraction of false positives by identifying blended eclipsing binary systems observed as composed spectra, asymmetric CCFs and/or stars with low surface gravities.

These data have been also useful for identifying unblended eclipsing binary systems where the computed RVs phase up well with the ephemeris determined from the light-curve analysis but show amplitudes that are too high to be produced by planetary mass companion. Some of these systems are very interesting because they include very low mass stars (VLMS) as components. Even though VLMS (0.08 \( M_\odot \) < \( M_* \) < 0.3 \( M_\odot \)) are the most common stars in our galaxy, there
are very few VLMS for which precise radii and masses have been determined and therefore the calibration of theoretical models of structure of these objects is quite poor. In this regard, we have published the discovery and precise physical parameters of four F-M eclipsing binary systems (Zhou et al. 2014b) and a 0.24 + 0.18 $M_\odot$ double-lined eclipsing binary (Zhou et al. 2015a) from the HATSouth survey, where part of the spectroscopic data was processed through our set of CERES pipelines.

However, the main achievement of the CERES pipelines is the confirmation of the planetary nature of the HATSouth candidates through precise RVs. These pipelines have been used to process spectroscopic data for all the 17 already published HATSouth TEPs (Penev et al. 2013; Mohler-Fischer et al. 2013; Bayliss et al. 2013; Jordán et al. 2014; Zhou et al. 2014a; Hartman et al. 2015b; Brahm et al. 2015b; Mancini et al. 2015; Bayliss et al. 2015; Bakos et al. 2015; Ciceri et al. 2015a; Brahm et al. 2015a) and also for other 30 systems that have been confirmed but which are being analysed or are close to be published. In particular, the development of a new pipeline for the FEROS spectrograph has played a key role in all the discoveries because this instrument is by far the one for which we obtain more observing time thanks to our collaborators from MPIA. As is shown in Figure 2.12, the RVs computed by the official data reduction software for FEROS allowed a very marginal detection of the Keplerian variation for typical Jupiter mass planets discovered by the HATSouth survey. Moreover, other systems with smaller RV semi-amplitudes were totally lost by that pipeline. On the other hand, the pipeline based on CERES is able to clearly detect the RV signals of HATS-2b and HATS-3b allowing a much more precise determination of the orbital parameters of the system including the planetary mass. Another example of the capabilities of our CERES pipeline to process FEROS data is shown in Figure 2.13, where a $K\approx40$ km/s orbital variation is measured for a relatively faint V=13.9 star. This system corresponds to a transiting hot Saturn-mass planet ($M_p \approx 0.3M_J$, $P=3.8$ days) that has not been published yet. HATSouth candidates that do not show RV vari-
ations at the 20 m/s level based on FEROS and Coralie observations are considered as strong Neptune-mass candidates that can then be confirmed with more powerful instruments like PFS, HIRES and/or HARPS, as was in done for the detections of HATS-7b and HATS-8b.

Figure 2.12: Top: RV measurements for HATS-2b obtained with the FEROS spectrograph as function of the orbital phase determined from the photometric ephemeris. The black points correspond to the RVs computed by the official pipeline while the red points are obtained with the CERES pipeline. Bottom: Same as the top panel but for HATS-3b.
2.8.2 Other results

Due to the high quality results that can be obtained with the CERES pipelines and the automation of the system, these reduction and analysis routines have been used to process echelle data in a variety of other research projects that we mention in the following paragraphs.

**Detached Eclipsing Binaries**

The importance of detached eclipsing binaries (DEB) relies in that model independent fundamental physical parameters can be obtained from them by combining photometric and spectroscopic observations. An ongoing project has been acquiring spectra for more than 3 years of DEBs discovered with the light curves of the All-Sky Automated Survey (ASAS) in order
to characterise in great detail those systems for testing theories of stellar formation and evolutionary models. The spectroscopic data of this project obtained with the FEROS, Coralie and PUCHEROS spectrographs have been processed with the pipelines we developed based on CERES routines and 2 of these systems have been published (Helminiak et al. 2014; Coronado et al. 2015).

More Extrasolar Planets

The precision of the RVs delivered by our pipelines allows to detect the gravitational pull that a giant planet induces on a star.

Our CAFE pipeline was used to spectroscopically monitor a sample of Kepler candidates and contributed in the discovery of KOI-372b (Mancini et al 2015), a giant TEP orbiting a young G-type star in an eccentric orbit with a period of 125 days that shows tentative transit timing variations (TTVs), which can be associated with the presence of another non-transiting giant planet.

Our FEROS pipeline has been recently used to process the data of the EXPRESS (EXoPlanets aRound Evolved StarS) survey (Jones et al. 2011), which focuses on the detection of giant planets orbiting giant stars with the RV method. Several systems monitored by this survey have started to show RV variations consistent with the presence of planetary-mass orbiting companions. For example, HD33844 is a K giant with two super-Jupiters in a 3:5 resonance orbit (Wittenmyer et al. 2015).

It is important also to monitor systems that have already detected planets for improving the stellar and planetary parameters and also for searching for additional companions. The study of Ciceri et al. (2015b) focused on the detailed characterisation of WASP-45 and WASP-46.
systems and the spectroscopic analysis of the FEROS spectra was performed with the CERES pipeline.

White Dwarf - Main Sequence binaries

Close binary systems composed by a white dwarf (WD) and a main sequence star are expected to be the progenitors of type Ia supernovae. Nonetheless, no systems like that have been discovered to date. In this context, there is a project running to detect such systems in which the candidates are identified by combining data from the Radial Velocity Experiment (RAVE) with UV data from the GALEX survey for selecting F, G and K type stars with significant UV excess. These candidates are then spectroscopically monitored with the echelle of the DuPont telescope and FEROS for detecting the orbital variation of the main sequence star produced by the WD. These data are processed with CERES, which has already led to the discovery of the first pre-supersoft X-ray binary (Parsons et al. 2015).

Novae

Novae are considered as probable sources for an important fraction of the lithium present in the Universe because the observed lithium abundance, for example in young stars, is significantly higher than the one predicted by Big Bang nucleosynthesis theories. However, the first detection of lithium in a nova was obtained from early spectra obtained with the PUCHEROS spectrograph of V1369 Cen. Given that the official PUCHEROS data reduction system is based on CERES, the spectra for this object were processed through our pipeline.
2.9 Summary

In this chapter we have presented CERES, which is a set of routines for the reduction, extraction and analysis of echelle spectra that can be used to build automated pipelines that allow to process data coming from different instruments in a uniform and homogeneous manner. Our algorithms are able to process all the data from scratch by doing typical CCD reductions steps, tracing of the echelle orders, optimally extracting the traces, performing wavelength calibration with a ThAr lamp or a Fabry Perot system and applying some analysis on the reduced spectra, like the computation of RVs and BSs from the CCF and a rough estimation of the stellar atmospheric parameters. We have developed robust pipelines for 10 echelle spectrographs with the principal goal of performing an efficient spectroscopic follow-up of TEP candidates from the HATSouth Survey. These processed data have allowed the confirmation of the planetary nature of 17 already published planets and of other ~30 systems that are being analysed or close to publication. Due to the excellent performance of our pipelines we have used them also for processing data of other projects with a wide range of scientific topics. CERES is mostly written in Python and we plan to make it public in the forthcoming months (github.com/rabrahm/ceres).
Chapter 3

ZASPE: A Code to Measure Stellar Atmospheric Parameters and their Covariance from Spectra

Abstract

We present the Zonal Atmospheric Stellar Parameters Estimator (ZASPE): a new algorithm, and associated code, for determining precise stellar atmospheric parameters and their uncertainties from high resolution echelle spectra of FGK-type stars. ZASPE estimates stellar atmospheric parameters by comparing the observed spectrum against a grid of synthetic spectra only in the spectral zones most sensitive to changes in the atmospheric parameters. Realistic uncertainties in the parameters are computed from the data itself, by taking into account the systematic mismatches between the observed spectrum and the best-fit synthetic one. The covariances be-

\footnote{based on Brahm, R., Jordán, A., Hartman, J., and Bakos, G., 2015, submitted to MNRAS}
tween the parameters are also estimated in the process. ZASPE can use any pre-calculated grid of synthetic spectra. We tested the performance of two existing libraries (Coelho et al. 2005; Husser et al. 2013) and we concluded that neither is suitable for computing precise atmospheric parameters. We describe a process to synthesise a new library of synthetic spectra that was found to generate consistent results with respect to parameters from the SWEET-Cat sample (Santos et al. 2013).

3.1 Introduction

The determination of the physical parameters of stars is a fundamental requirement for studying their formation, structure and evolution. Additionally, the physical properties of extrasolar planets depend strongly on how well we have characterised their host stars. In the case of transiting planets, the measured transit depth is related to the ratio of the planet to stellar radii. Similarly, for radial velocity planets the semi-amplitude of the orbit is a function of both the mass of the star and the mass of the planet. In the case of directly imaged exoplanets, their estimated masses depend on the age of the systems. With more than 2000 planets and planetary candidates discovered, mostly by the Kepler mission (Howard et al. 2012; Burke et al. 2014), homogeneous and accurate determination of the physical parameters of the host stars are required for linking their occurrence rates and properties with different theoretical predictions (Howard et al. 2010; Buchhave et al. 2014).

Direct determinations of the physical properties of single stars (mass, radius and age) are limited to a couple dozens of systems. Long baseline optical interferometry has been used on bright sources with known distances to measure their physical radii (Boyajian et al. 2012, 2013) and precise stellar densities have been obtained using asteroseismology on stars observed by Kepler and CoRoT (Silva Aguirre et al. 2015). Unfortunately, for the rest of the stars, includ-
ing the vast majority of planetary hosts, physical parameters cannot be measured and indirect procedures have to be adopted in which the atmospheric parameters, such as the effective temperature \( (T_{\text{eff}}) \), surface gravity \( (\log g) \) and metallicity \( ([\text{Fe/H}] ) \), are derived from stellar spectra by using theoretical model atmospheres. Stellar evolutionary models are then compared with the estimated atmospheric parameters in order to determine the physical parameters of the star.

The amount of information about the properties of the stellar atmosphere contained in its spectrum is enormous. The presence, strength and shape of the numerous absorption lines depend on the temperature and pressure conditions at the layers of the photosphere where the lines are generated and also on the amount of absorbers available. Current state-of-the-art high resolution echelle spectrographs are capable of detecting subtle variations of spectral lines which, in principle, can be translated into the determination of the physical atmospheric conditions of a star with exquisite precision. However, there are several factors that reduce the precision that can be achieved. These factors can be divided into two groups. On one side there are many other properties of a star that can produce changes on the absorption lines. For example, velocity fields on the surface of the star, which include the stellar rotation (which may be differential) and the micro and macro turbulence, modify the shape of the absorption lines. Non-solar abundances change the particular strength of the lines of each element. The inclusion of all these variables as free parameters makes the problem very demanding on computing resources and even if all known parameters are accounted for, the second group of factors will still fundamentally limit the precision of the estimated parameters. This second group of factors includes the imperfect modelling of the stellar atmospheres and spectral features due to unknown opacity distribution functions, uncertainties in the properties of particular atomic and molecular transitions, effects arising from the assumed geometry of the modelled atmosphere and non-LTE effects. The first group of factors can be controlled in some way by treating them as free parameters or by adopting some empirical or theoretical model that assumes that some of these parameters are
functions of the stellar atmospheric parameters. However, the systematic uncertainty produced by the second group of factors is unavoidable and is the principal problem for obtaining reliable uncertainties in the estimated stellar parameters. These uncertainties then propagate to the planetary parameters and can bias the results or hide potential trends in the properties of the system under study that, if detectable, could lead to deeper insights into their formation and evolution.

There are two main procedures which have been adopted for estimating atmospheric stellar parameters using high resolution spectra. The first one uses the principles of excitation and ionisation equilibria given by the Boltzmann and Saha equations. The abundance of one particular element measured on different absorption lines must be the same. Since Fe is the element with more lines present in the spectra of FGK-type stars, commonly the equivalent widths of FeI and FeII lines are used to measure $T_{\text{eff}}$ and $\log g$, respectively (e.g. Santos et al. 2013). The advantages of this technique rest on its simplicity, direct astrophysical foundations and low degeneracies between the estimated parameters, but it is less suitable for stars with moderate rotation ($v \sin i > 10$ km s$^{-1}$) and/or low temperatures ($T_{\text{eff}} < 5000$ K) due to effects related to the blending of absorption lines. Due to the small amount of lines used by this technique, it is also not suitable for low signal to noise spectra and/or data with moderate spectral resolution. The uncertainties on the parameters are obtained from the dispersion of the Fe lines in the fit and therefore do not include the systematic uncertainty on the transition parameters due to imperfect modelling.

The second procedure consists in comparing the observed spectra against synthetic models and adopting the parameters of the model that produces the best match as the estimated atmospheric parameters of the observed star. This technique has been implemented in algorithms such as SPC (Buchhave et al. 2012) and SME (Valenti & Piskunov 1996) to derive parameters of planetary host stars. Thanks to the large number of spectral features used, this method has been shown to
be capable of dealing with spectra having low SNR, moderate resolution and a wide range of stellar atmospheric properties. However, one of the major drawbacks of spectral synthesis methods for the estimation of the atmospheric parameters is the determination of their uncertainties. This problem arises because the source of error is not the Poisson noise of the observed spectrum, but instead is governed by imperfections in the synthesised model spectra, which produce highly correlated residuals. In such cases standard procedures for computing uncertainties for the parameters are not reliable. For example, SPC computes the internal uncertainties using the dispersion from different measurements in the low SNR regime, but an arbitrary floor is applied when the uncertainties are expected to be dominated by the systematic miss-matches between models and data. Additionally, Torres et al. (2012) showed that there are strong correlations between the atmospheric parameters obtained using spectral synthesis techniques, and therefore, the covariance matrix of the parameters should be a required output of any stellar parameter classification tool so that the uncertainty of its results are properly propagated to the posterior inferences that are made using them. Recently, Czekala et al. (2014) introduced Starfish, a code that allows robust estimation of stellar parameters using synthetic models by using a likelihood function with a covariance structure described by Gaussian processes. Starfish allows robustness to synthetic model imperfections through a principled approach using a sophisticated likelihood function and provides full posterior distributions for the parameters, but as we will argue later its uncertainties are significantly underestimated.

In this chapter we present a new algorithm, dubbed Zonal Atmospheric Stellar Parameters Estimator (hereon ZASPE), for estimating stellar atmospheric parameters using the spectral synthesis technique. The uncertainties and correlations in the parameters are computed from the data itself and include the systematic mismatches due to the imperfect nature of the theoretical spectra. The structure of the paper is as follows. In Section 3.2 we describe the method that ZASPE uses for determining the stellar parameters and their covariance matrix, including details on the
synthesis of a new synthetic library to overcome limitations of the existing libraries for stellar parameter estimation. In Section 3.3 we summarise the performance of ZASPE on a sample of stars with measured stellar parameters, and we compare our uncertainties with those produced by Starfish. Finally, in Section 3.4 we summarize and conclude.

3.2 The Method

In order to determine the atmospheric stellar parameters of a star, ZASPE compares an observed continuum normalised spectrum against synthetic spectra using least squares minimisation by performing an iterative algorithm that explores the complete parameter space of FGK-type stars. For simplicity, we assume first that we are able to generate an unbiased synthetic spectrum with any set of stellar atmospheric parameters ($T_{\text{eff}}$, $\log g$ and [Fe/H]). By unbiased we mean that there are no systematic trends in the level of mismatch of the synthesised and real spectra as a function of the stellar parameters, but there can be systematic mismatches that are not a function of stellar parameters. If $F_\lambda$ is the observed spectrum and $S_\lambda(\tilde{\theta})$ is the synthesised spectrum with parameters $\tilde{\theta} = [T_{\text{eff}}, \log g, \text{[Fe/H]}]$, the quantity that we minimize is

$$X^2(\tilde{\theta}) = \sum_\lambda |F_\lambda - S_\lambda(\tilde{\theta})|^2.$$  \hspace{1cm} (3.1)

We have not considered the flux uncertainties in Equation 3.1 because we are assuming that the signal to noise ratio (SNR) of the data is high enough for the uncertainties in the parameters to be dominated by systematics, which is generally the case for spectra having SNR $\geq 30$ per resolution element.

The synthesised spectrum needs to have some processing done in order to compare it against the observed one. We do not treat microturbulence and macroturbulence as free parameters, but
instead we assume that these values are functions of the atmospheric parameters. The microturbulence value is required during the process of synthesising the spectra and it depends on the particular spectral library selected to do the comparison (see Section 3.2.5). On the other hand, the macroturbulence degradation is applied after the synthetic spectra have been generated. We compute the macroturbulence value for each synthetic spectrum from its $T_{\text{eff}}$ using the empirical relation given in Valenti & Fischer (2005)\textsuperscript{2}, namely:

$$v_{\text{mac}} = \left(3.98 + \frac{T_{\text{eff}} - 5770\ K}{650\ K}\right)\text{km s}^{-1}$$

(3.2)

The effect of macroturbulence on the spectrum is given by a convolution with a Gaussian kernel whose standard deviation is given by $\sigma_{\text{mac}} = 0.297 \ v_{\text{mac}}$, as was approximated in Takeda et al. (2008). The degradation to the particular instrumental resolution, $R = \Delta \lambda / \lambda$, is performed by convolving the synthetic spectrum with another Gaussian kernel whose standard deviation is $\sigma_{\text{res}} = \lambda / (2.3\ R)$. The model spectrum is then split according to the echelle orders of the observed spectrum and the pixelization effect is taken into account by integrating the synthetic flux over each wavelength element of the observed spectrum. Finally, each echelle order of the observed and synthetic spectra is continuum normalised by fitting a low degree polynomial whose order is defined by the user.

### 3.2.1 The sensitive zones

One of the novel features of ZASPE in contrast to other similar codes, is that the comparison between the observed and synthetic spectra is performed in particular optimized wavelength zones, rather than using the full spectrum. These zones correspond to the most sensitive regions of the spectra to changes in the stellar parameters and are redefined in each iteration of ZASPE.\textsuperscript{2} As was pointed out by Torres et al. (2012), the formula in Valenti & Fischer (2005) has a wrong sign.
These sensitive regions are determined from the approximate gradient of the modelled spectra with respect to the stellar parameters at $\bar{\theta}$, where $\bar{\theta} = \{T_{\text{eff}}^c, \log g^c, [Fe/H]^c\}$ is the set of parameters that produced the minimum $\chi^2$ in the previous iteration. In practice, once $\bar{\theta}$ is determined, ZASPE computes the following finite differences:

\[
\begin{align*}
\Delta S^1_{T_{\text{eff}}} &= ||S_A(T_{\text{eff}}^c + 200, \log g^c, [Fe/H]^c) - S_A(\bar{\theta})||, \\
\Delta S^2_{T_{\text{eff}}} &= ||S_A(T_{\text{eff}}^c - 200, \log g^c, [Fe/H]^c) - S_A(\bar{\theta})||, \\
\Delta S^1_{\log g} &= ||S_A(T_{\text{eff}}^c, \log g^c + 0.3, [Fe/H]^c) - S_A(\bar{\theta})||, \\
\Delta S^2_{\log g} &= ||S_A(T_{\text{eff}}^c, \log g^c - 0.3, [Fe/H]^c) - S_A(\bar{\theta})||, \\
\Delta S^1_{[Fe/H]} &= ||S_A(T_{\text{eff}}^c, \log g^c, [Fe/H]^c + 0.2) - S_A(\bar{\theta})||, \\
\Delta S^2_{[Fe/H]} &= ||S_A(T_{\text{eff}}^c, \log g^c, [Fe/H]^c - 0.2) - S_A(\bar{\theta})||,
\end{align*}
\] (3.3) (3.4) (3.5) (3.6) (3.7) (3.8)

from which the approximate gradient of the synthesised spectra with respect to the atmospheric parameters, averaged on the three parameters, is estimated as

\[
\Delta S_A(\bar{\theta}) = \frac{1}{6}(\Delta S^1_{T_{\text{eff}}} + \Delta S^2_{T_{\text{eff}}} + \Delta S^1_{\log g} + \Delta S^2_{\log g} + \Delta S^1_{[Fe/H]} + \Delta S^2_{[Fe/H]}).
\] (3.9)

Spectral regions where $\Delta S_A(\bar{\theta})$ is greater than an arbitrary threshold defined by the user are identified as the sensitive zones, which we denote as $[z_i]$. Figure 3.1 shows a portion of an observed spectrum and the sensitive zones selected in the final ZASPE iteration. It can be seen that the selected sensitive zones correspond to the spectral regions where absorption lines are present, but that not all the absorption lines are identified as sensitive zones at a given threshold.

The introduction of the zones into the problem allows also the rejection of portions of the spectra
Figure 3.1: Portion of a high resolution echelle spectrum of a solar type star. The coloured bars are the regions that ZASPE determines as the most sensitive zones of the spectrum to changes in the atmospheric parameters. These zones in general correspond to prominent absorption lines but some lines are not selected either due to the fact that the changes in their profiles are too small in response to changes in atmospheric parameters around the best value in a given iteration, or due to strong mismatches with the best synthetic spectrum.
that strongly deviate from $S_d(\vec{\theta})$, due to modelling problems or by the presence of artifacts in the data that remain in the spectrum (e.g., cosmic rays, bad columns). Once the sensitive zones are known, ZASPE builds a binary mask, $M_d$, filled with ones in the spectral range of the sensitive zones and zeros elsewhere, i.e.

$$M_d = \begin{cases} 
1 : \lambda \in \{z_d\} \\
0 : \lambda \notin \{z_d\}
\end{cases} \quad (3.10)$$

For the next iteration, the function to be minimised will be

$$X^2(\vec{\theta}) = \sum_d M_d(F_d - S_d(\vec{\theta}))^2. \quad (3.11)$$

In the first iteration of ZASPE the complete spectral range is utilised and $M_d \equiv 1$.

### 3.2.2 Radial Velocity and $v \sin i$

In each ZASPE iteration, the search of the $X^2$ minimum is performed simultaneously over the three atmospheric parameters. However, the velocity of the observed spectrum with respect to the synthesised spectra and the $v \sin i$ value are determined in each iteration after $\vec{\theta}$ is determined by computing the cross correlation function between the observed spectrum and the synthesised one with parameters $\vec{\theta}$ and $v \sin i = 0$ km s$^{-1}$. The cross correlation function is given by

$$CCF(v, 0) = \int M_d F_d S_{d'}(\vec{\theta}, 0) d\lambda, \quad (3.12)$$

where $\lambda'$ is the wavelength Doppler shifted by a velocity $v$, given in the non-relativistic regime by $\lambda' = \lambda + \lambda v/c$, where $c$ is the speed of light. A Gaussian function is fitted to the CCF and the mean of the Gaussian is assumed as the radial velocity of the observed spectrum while the $v \sin i$ is determined from the full with at half maximum (FWHM) of the CCF as follows. New CCFs are computed between the synthetic spectrum without rotation and the same synthetic spectrum
degraded by different amounts of $v \sin i$:

$$CCF(v, v \sin i) = \int M_{\lambda} S_{\lambda}(\vec{\nu}, v \sin i)S_{\nu}(\vec{\nu}, 0)d\lambda$$ (3.13)

The FWHM is computed for each CCF peak and a cubic spline is fitted to the relation between the FWHM and $v \sin i$ values. This cubic spline is then used to interpolate the $v \sin i$ of the observed spectra from the FWHM of the CCF computed in equation 3.12.

In the next ZASPE iteration all the synthesised spectra are Doppler shifted in wavelength by RV and are degraded to the $v \sin i$ obtained in the previous iteration. The degradation of the spectrum by the rotation is performed with a rotational kernel computed following eq. 18.11 of Gray (2008). The limb darkening is taken into account using the quadratic limb-darkening law with coefficients for the appropriate stellar parameters calculated using the code from Espinoza & Jordán (2015). The $v \sin i$ value for the first ZASPE iteration is obtained by cross-correlating the observed spectrum against one with stellar parameters similar to those of the Sun.

3.2.3 Grid exploration

The synthesis of high resolution spectra is a computationally intensive process. For this reason ZASPE uses a pre-computed grid of synthetic spectra and, in order to obtain a synthetic spectrum for an arbitrary set of stellar parameters, a cubic multidimensional interpolation is performed.

Given the known correlations between the three atmospheric parameters we aim to estimate and the possibility of existence of secondary minima in $X^2$ space, the approach of ZASPE for finding the global $X^2$ minimum is to explore the complete parameter space covered by the grid and not to rely on slope minimisation techniques that require an initial set of guess parameters as is required for example in SME.
In each ZASPE iteration the extension and spacing of the parameter grid being explored changes. In the first iteration ZASPE explores the complete atmospheric parameter grid with coarse spacing, while from the fourth iteration on, ZASPE starts focusing on smaller regions of parameter space around $\bar{\theta}$ which are densely explored. Table 3.1 shows the extension and spacings that ZASPE uses for each iteration in its default version, but these values can be easily modified by the user.

ZASPE terminates the iterative process when the parameters obtained after each iteration do not change by significant amounts. In detail, convergence is assumed to be reached when the parameters obtained in the $i$-th iteration do not differ by more than 10 K, 0.03 dex and 0.01 dex in $T_{\text{eff}}$, $\log g$ and $[\text{Fe/H}]$, respectively, from the ones obtained in the $(i - 1)$-th iteration. This convergence is usually achieved after $\sim 5 - 10$ iterations.

### 3.2.4 Parameter uncertainties and correlations

As we mentioned in Section 3.1, one major issue of the algorithms that use spectral synthesis methods for estimating the stellar atmospheric parameters is the problem of obtaining reliable estimates of the uncertainties in the parameters and their covariances. ZASPE deals with this problem by assuming that the principal source of errors is the systematic mismatch between the observed spectrum and the synthetic one. The top panel of Figure 3.2 shows a portion of a high resolution spectrum of a star and the synthetic spectrum that produces the best match with the data. Even though each absorption line is present in both spectra, the depth of the lines are frequently different. This systematic mismatch can be further identified in the bottom panel of Figure 3.2, where the residuals in the regions of the absorption lines can be seen to be in several cases significantly greater than those expected just from photon noise. In addition, the residuals are clearly non-Gaussian and highly correlated in wavelength.
Table 3.1: Grid extension and spacing for each ZASPE iteration.

<table>
<thead>
<tr>
<th>Iteration</th>
<th>$T_{\text{eff}}$ [K]</th>
<th>$\Delta T_{\text{eff}}$ [K]</th>
<th>log $g$</th>
<th>$\Delta$ log $g$</th>
<th>$[\text{Fe}/\text{H}]$</th>
<th>$\Delta[\text{Fe}/\text{H}]$</th>
</tr>
</thead>
<tbody>
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<td>1</td>
<td>4000</td>
<td>0</td>
<td>1.0</td>
<td>0.5</td>
<td>0.6</td>
<td>0.5</td>
</tr>
<tr>
<td>2</td>
<td>7000</td>
<td>-500</td>
<td>5.0</td>
<td>-1.0</td>
<td>-0.6</td>
<td>0.1</td>
</tr>
<tr>
<td>3</td>
<td>10000</td>
<td>-300</td>
<td>0.6</td>
<td>0.6</td>
<td>0.1</td>
<td>0.05</td>
</tr>
<tr>
<td>4</td>
<td>13000</td>
<td>-200</td>
<td>0.4</td>
<td>0.2</td>
<td>0.05</td>
<td>0.006</td>
</tr>
<tr>
<td>&gt; 4</td>
<td>$T_{\text{eff}}$ + 50</td>
<td>$\Delta T_{\text{eff}}$ + 50</td>
<td>0.2</td>
<td>0.05</td>
<td>0.05</td>
<td>0.02</td>
</tr>
</tbody>
</table>
Figure 3.2: Top: portion of a high resolution echelle spectrum of a star (continuum line) and the synthetic spectrum that produces the best match with the data (dashed line). Bottom: residuals between the two spectra and average 3σ errors expected from photon noise. Both panels show that the synthetic spectrum that best fits the data produces systematic mismatches in the zones of the absorption lines and that the errors are greater than the ones expected from the received flux.
Our approach to take into account the systematic mismatches, which builds upon the approach of Grunhut (2009), is to define a random variable $D_i$ which is responsible for modifying the strength of each absorption feature in a sensitive zone $z_i$ of the synthesised spectrum. If $S_p'$ is a perfect synthetic spectrum in the $i$-th sensitive zone $z_i$, given a probability density $P(D)$ for the random variable $D$ we can generate an imperfect synthetic spectrum $S_n$ as

$$ S_n = (S_p' - 1)D + 1. \quad (3.14) $$

An estimate of the probability density function $P(D)$ can be obtained from the data itself by computing the set of mismatch factors, $d_{zi}$, between the data and the optimal synthetic spectrum in each sensitivity zone as

$$ d_{zi} = \frac{F_{zi} - 1}{S_n - 1}. \quad (3.15) $$

Figure 3.3 shows a histogram of the mismatch factors for the same spectrum of Figure 3.2 but for a greater wavelength coverage (5000 $\AA < \lambda < 6000$ $\AA$). The distribution of mismatch factors is pretty symmetric, centred around $d_{zi} = 1$, and shows a wide spread of values. Several absorption lines of the synthetic spectrum that best fits the data can have values that are double or half the strength of the observed ones. Some lines could deviate even more, however, these zones are rejected as strong outliers by ZASPE. Outliers are identified by computing the root mean square (RMS) of the residuals between the observed spectra and the optimal synthetic one in each sensitive zone and zones with RMS values greater than 3 times the average RMS value are rejected.

ZASPE determines the probability distribution of the stellar atmospheric parameters by running a random sampling method where a synthetic spectrum that produces the minimum $X^2$ is searched again a number $B$ of realizations in the same way as described in the previous sections, but using a modified set of model spectra in each realization. The only difference between the
Figure 3.3: Histogram of the mismatch factors in the sensitive zones. In several regions of the spectrum the absorption lines of the synthetic spectrum can strongly deviate from the ones of the observed one.
minimization run on each realization and the original search is that the set of sensitive zones \( \{z_i\} \) is kept fixed at the set that ZASPE converged to. In each replication, the strength of the lines of the synthetic spectra are modified by randomly selecting mismatch factors from the \( \{d_z\} \) set, with replacement. Each sensitive zone is modified by a different factor which can be repeated, but the same factor is applied in each zone for the whole set of synthesised spectra. In the random sampling method, the quantity that is minimised on each iteration \( b \) is

\[
X_b^2 = \sum_{A} M_A [F_A - (S_A(\vec{D}) - 1)D_A + 1]^2
\]

(3.16)

where \( D_A \) is a mask defined for each realisation and contains the mismatch factors for each sensitive zone. In order to avoid possible biases in the final distribution of the parameters originating from the asymmetry in the sampling function, when a factor is selected from \( \{d_z\} \) we include a 0.5 probability for this factor to take its reciprocal value, enforcing in practice symmetry in the function from which the factors are sampled. After each realisation of the sampling method a new set of atmospheric parameters is found. From these sets of possible outcomes, the complete covariance matrix of the atmospheric parameters can be estimated. After testing the method on spectra with different stellar atmospheric parameters we found that about \( B = 100 \) realisations are enough to obtain reliable parameter covariance matrices.

The procedure that ZASPE uses to obtain the errors and correlations assumes that the systematic mismatches between the different zones are uncorrelated. This simplification of the problem means that some systematic errors between the data and the models are not accounted for by our method. For example, if the abundance of one particular atomic species strongly deviates from the one assumed in our model, the degree of mismatch of the absorption lines of that element will be correlated. However, in Section 3.3 we will find that our assumption is able to account for the typical value of systematic errors in atmospheric parameters, as inferred from measuring the parameters with different methods.
3.2.5 The reference spectral synthetic library

In order to determine the atmospheric stellar parameters of a star, ZASPE compares the observed spectrum against a grid of synthetic models. In principle, after some minor specifications about the particular format of the grid, ZASPE can use any pre-calculated grid. We have tested ZASPE with two publicly available grids of synthetic spectra: the one of Coelho et al. (2005, hereafter C05), which are based on the ATLAS model atmospheres (Kurucz 1993); and the one presented in Husser et al. (2013, hereafter H13), which is based on the Phoenix model atmospheres. We have found that both grids present important biases when comparing the stellar parameters obtained using them with ZASPE for a set of reference stars. In Figure 3.4 we show the comparison of the results obtained by ZASPE against the values presented in SWEET-Cat (Santos et al. 2013) for a set of publicly available spectra in the ESO archive.

SWEET-Cat is a catalogue of atmospheric stellar parameters of planetary host stars. The parameters were computed using the equivalent width method and the ATLAS plane-parallel model atmospheres (Kurucz 1993) on a set of high signal to noise and high spectral resolution echelle spectra. We decided to use SWEET-Cat for benchmarking our method because: (1) it includes stars with a wide diversity of stellar parameters; (2) the same homogeneous analysis is applied to each spectrum; (3) the equivalent width method has clear physical foundations and does not produce strong correlations between the inferred parameters; and (4) the inferred parameters have proven to be consistent with results obtained with different, less model-dependent methods (infrared flux, interferometry, stellar density computed from transit light-curve modelling) and also with standard spectral synthesis tools SPC and SME (Torres et al. 2012).

The top panels of Figure 3.4 show the comparison of the results obtained by ZASPE using the H13 library. These results deviate strongly from the reference values for the three atmospheric
parameters. The parameters are systematically underestimated by 300 K, 0.6 dex and 0.3 dex on average in $T_{\text{eff}}$, log g and [Fe/H], respectively. There also appear to be quadratic trends in $T_{\text{eff}}$ and log g which produce greater deviations for hot and/or giant stars. These systematic trends can be expected from this kind of grid of synthetic spectra because the parameters of the atomic transitions come from theory or from laboratory experiments, and are not empirically calibrated with observed spectra.

Another possible source for these strong biases can be related to the different model atmospheres used. We have estimated the atmospheric parameters of the Sun with ZASPE+H13 finding that they present important deviations with respect to the accepted reference values ($T_{\text{eff}}^{H13}=5430$ K, log g$_{H13}^{H13}=4.1$ dex, [Fe/H]$_{H13}^{H13}=-0.3$ dex). These results show that if the strong observed biases are produced due to the use of different model atmospheres, the PHOENIX models are less precise than the ATLAS ones for estimating atmospheric parameters.

The central panels of Figure 3.4 correspond to the results obtained by ZASPE using the C05 library. Even though the average values determined with the C05 grid are more compatible with the reference values than the ones obtained with the H13 grid, there is a strong trend in $\Delta T_{\text{eff}}$. The systematic trend tends to bring the values of $T_{\text{eff}}$ towards the one of the Sun ($\approx 5750$K) and can produce deviations of $\approx 500$ K for F-type stars. In this case both sets of results are obtained using the same model atmospheres. The origin of the observed bias is unknown, but it can be plausibly related to two procedures that were adopted in the generation of the C05 grid. First, the oscillator strengths (log gf) of several Fe transitions were calibrated using a high resolution spectrum of the Sun, which could bias the results if the physical processes responsible for the formation of the lines are not accurately modelled by the synthesising program; and second, all the spectra with log g > 3.0 were synthesised assuming a solar micro turbulence value of $v_t = 1.0$ km s$^{-1}$, but FGK-dwarfs have measured microturbulence values in the range of $\approx 0$-
6 km s$^{-1}$. The behaviour obtained for the values of the other parameters shows less biases. However, the trend in $T_{\text{eff}}$ coupled with the correlations in the atmospheric parameters induce an important dispersion in log $g$ and [Fe/H] too.

### 3.2.6 A new synthetic grid

As shown in the last section, it is not straightforward to use public libraries of synthetic spectra for estimating atmospheric parameters of stars due to the strong systematic trend and biases that can arise due to erroneous physical assumptions and calibrations. For that reason we decided to synthesise a new grid. We used the spectrum code (Gray 1999) and the Kurucz model atmospheres (Castelli & Kurucz 2004) with solar abundances. In order to avoid biases in $T_{\text{eff}}$ related to assuming a fixed microturbulence value we assume that the microturbulence is a function of $T_{\text{eff}}$ and log $g$. Ramírez et al. (2013) established an empirical calibration of the microturbulence as a function of the three atmospheric parameters but the validity of the proposed relation was limited to stars having $T_{\text{eff}} > 5000$ K. We thus decided to base our microturbulence calibration on the values computed in SWEET-Cat by Santos et al. (2013). For dwarf stars (log $g > 3.5$) the microturbulence was assumed to depend on $T_{\text{eff}}$ by a third degree polynomial, while for sub-dwarf and giant stars the micro turbulence was fixed to two different values as follows

\[
v_t = -36.125 + 0.019 T_{\text{eff}} - 3.65 \times 10^{-6} T_{\text{eff}}^2 + 2.28 \times 10^{-10} T_{\text{eff}}^3 \text{ km s}^{-1}, \quad (\log g > 3.5)
\]

\[
v_t = 1.2 \text{ km s}^{-1}, \quad (3.0 < \log g < 3.5)
\]

\[
v_t = 1.6 \text{ km s}^{-1}. \quad (\log g < 3.0)
\]

We used the line list provided in the spectrum code. However, we tuned the log $gf$ of several
Figure 3.4: Comparison of the atmospheric parameters obtained by ZASPE using three different libraries of synthetic spectra against the values reported in SWEET-Cat. The top panels correspond to the results obtained using the H13 grid, where strong biases and systematic trends are present in the three parameters probably because the parameters of the atomic transitions were not empirically calibrated. The central panels correspond to the results obtained using the C05 grid, where a strong systematic trend in $T_{\text{eff}}$ drives $T_{\text{eff}}$ values towards that of the Sun. The bottom panels show the results obtained by ZASPE when using the synthetic library presented in this work. Results are compatible with the values reported in SWEET-Cat and no strong systematic trends can be identified.
prominent atomic lines using the spectra of a set of standard stars that have $T_{\text{eff}}$ values measured via interferometry (Boyajian et al. 2012, 2013) and public FEROS spectra in the ESO archive. Table 3.2 shows the stars that were used to adjust the $\log gf$ values. The damping constants of the MgIb triplet and NaI doublet were also manually adjusted using the same set of standard stars. spectrum uses the classical van der Waals formulation to generate the wings of the strong lines but this procedure has been found to underestimate the strength of the absorption features. A common solution is to include an enhancement factor to correct for this behaviour. In our case, we determined this empirical fudge factor for each of these strong lines using the above mentioned set of standard stars. We found that the fudge factor has a temperature dependence. Anstee & O'Mara (1991) developed a detailed approximation of the van der Waals theory in which the temperature dependence of the damping constant was determined to follow a power law. In our case, we empirically treated the temperature dependence of the damping constants by fitting linear relations to the enhancement factors determined from the standard stars as a function of the temperature for each strong line. These parameters were then used to synthesise the MgIb and NaI lines for spectra with different values of $T_{\text{eff}}$.

The spectral range of our grid goes from 4900 Å to 6100 Å. This range was selected because most of the spectral transitions for FGK-type stars are located at shorter wavelengths than 6000 Å but for $\lambda < 5000$ Å spectral lines become excessively crowded which complicates the process of adjusting the $\log gf$ values. The grid limits and spacings of the stellar parameters of the grid we synthesised are

- $T_{\text{eff}}$: 4000K — 7000K, $\Delta T_{\text{eff}}$=200 K
- $\log g$: 1.0 dex — 5.0 dex, $\Delta T_{\text{eff}}$= 0.5 dex
- $[\text{Fe/H}]$: -1.0 dex — 0.5 dex, $\Delta T_{\text{eff}}$=0.25 dex.
We used a multidimensional cubic spline to generate the model atmospheres with atmospheric parameters not available in the original set of atmospheres provided by the Kurucz models.

The bottom panels of Figure 3.4 show the results obtained using ZASPE with this new grid of synthetic spectra against the values stated in SWEET-Cat. The results agree very well with the reference values and no evident trends are present. The $T_{\text{eff}}$ shows an excellent agreement with only two outliers present. The results obtained for log $g$ have some tentative systematic trends. In particular, we note that SWEET-Cat report some log $g$ values greater than 4.7 dex, but we note that surface gravities higher than that are not common for FGK-type stars so those values are suspect. The [Fe/H] present no offset trends, but a systematic bias can be identified. [Fe/H] values are on average underestimated by 0.05 dex as compared to the SWEET-Cat values. However, differences of $\approx 0.09$ dex in [Fe/H] have been previously reported when comparing SWEET-Cat metallicities against the ones computed with the ones obtained via spectral synthesis techniques, so the offset we observe is within the expected range given the different techniques used (Mortier et al. 2013). In order to be consistent with SWEET-Cat, from here on we add 0.05 dex to the [Fe/H] values determined by ZASPE using this particular grid.

### 3.3 Performance

As an example of the performance of ZASPE, we present here the results we obtain when using it to analyse the spectra of the Sun and Arcturus. The spectra of these two objects have been studied extensively and they are used commonly to calibrate and validate spectral studies of stars. We obtained raw data from the ESO archive for both stars observed with the FEROS spectrograph (Kaufer & Pasquini 1998). We processed them through an automated reduction and extraction pipeline we have developed for FEROS and other spectrographs (Jordán et al.
Table 3.2: Sample of stars with temperatures measured using interferometric observations that were used to empirically calibrate log gf values and damping constants of prominent absorption lines.

<table>
<thead>
<tr>
<th>Name</th>
<th>$T_{\text{eff}}$ [K]</th>
<th>$\sigma_{T_{\text{eff}}}$ [K]</th>
<th>log $g$</th>
<th>[Fe/H]</th>
</tr>
</thead>
<tbody>
<tr>
<td>GJ105</td>
<td>4662</td>
<td>17</td>
<td>4.52</td>
<td>-0.08</td>
</tr>
<tr>
<td>GJ166A</td>
<td>5143</td>
<td>14</td>
<td>4.54</td>
<td>-0.24</td>
</tr>
<tr>
<td>GJ631</td>
<td>5337</td>
<td>41</td>
<td>4.59</td>
<td>0.04</td>
</tr>
<tr>
<td>HD102870</td>
<td>6132</td>
<td>26</td>
<td>4.11</td>
<td>0.11</td>
</tr>
<tr>
<td>HD115617</td>
<td>5538</td>
<td>13</td>
<td>4.42</td>
<td>0.01</td>
</tr>
<tr>
<td>HD142860</td>
<td>6294</td>
<td>29</td>
<td>4.18</td>
<td>-0.19</td>
</tr>
<tr>
<td>HD20630</td>
<td>5776</td>
<td>81</td>
<td>4.53</td>
<td>0.0</td>
</tr>
<tr>
<td>HD222368</td>
<td>6288</td>
<td>37</td>
<td>3.98</td>
<td>-0.08</td>
</tr>
<tr>
<td>HD22484</td>
<td>5997</td>
<td>44</td>
<td>4.07</td>
<td>-0.09</td>
</tr>
<tr>
<td>HD30652</td>
<td>6516</td>
<td>19</td>
<td>4.30</td>
<td>-0.03</td>
</tr>
<tr>
<td>HD39587</td>
<td>5961</td>
<td>36</td>
<td>4.47</td>
<td>-0.16</td>
</tr>
<tr>
<td>HD4628</td>
<td>4950</td>
<td>14</td>
<td>4.63</td>
<td>-0.22</td>
</tr>
</tbody>
</table>

2014, Brahm et al. in prep). The grid of synthetic spectra used by ZASPE in this analysis was generated by us and is described in Section 3.2.6. The spectral range selected for analysing the data was from 5000 to 6000 Å, which ensures a great amount of spectral transitions including the Mglb triplet, which is the most pressure sensitive feature for dwarf stars. Figures 3.5 and 3.6 summarize the results we obtain. The left panels show Hess diagrams in various planes using the outcome of the random sampling realisations, while the right panels show the marginalised distribution functions of the stellar atmospheric parameters. The best fit parameters are marked with crosses in the panels on the left and vertical lines in the ones on the right. Reference values of the stellar parameters are marked with circles in the panels on the left and dashed lines in the ones on the right.

In the case of the Sun the best fit parameters and errors we obtained were: $T_{\text{eff}}=5818 \pm 59$ K, log $g=4.49 \pm 0.09$ dex and [Fe/H]=0.01 ± 0.04 dex. These results are compatible with the accepted parameters of the Sun being 0.8σ, 0.6σ and 1σ apart in $T_{\text{eff}}$, log $g$ and [Fe/H],
respectively. The results obtained for Arcturus were: \( T_{\text{eff}} = 4331 \pm 63 \text{ K} \), \( \log g = 1.68 \pm 0.25 \text{ dex} \) and \([\text{Fe/H}] = -0.48 \pm 0.09 \text{ dex}\). In Figure 3.6 we include the parameters computed by Meléndez et al. (2003) which are compatible with the results obtained by ZASPE at the 1\( \sigma \) level.

In both cases, ZASPE shows there is a wide spread of possible outcomes which confirms the idea that the principal source of uncertainty is the imperfect modelling of the synthesised spectra. The uncertainties in the parameters that ZASPE reports are computed from the standard deviation of the values obtained in the random sampling simulations. The uncertainties in the parameters we found for the Sun are smaller than the ones found for Arcturus. This serves to illustrate that the amplitude of the uncertainty in the atmospheric parameters varies with spectral type, and that the synthetic grid we used has a better calibration for dwarf stars than for giant stars. It is therefore not accurate to adopt universal minimum uncertainties, as is often done in the literature.

The left panels of Figures 3.5 and 3.6 also show the existence of strong correlations between the parameters. The Pearson correlation coefficients \( \rho \) between the parameters in the case of the Sun are: \( \rho_{T_{\text{eff}}-\log g} = 0.63 \), \( \rho_{T_{\text{eff}}-[\text{Fe/H}]} = 0.89 \) and \( \rho_{\log g-[\text{Fe/H}]} = 0.49 \). For Arcturus the correlations we found are \( \rho_{T_{\text{eff}}-\log g} = 0.95 \), \( \rho_{T_{\text{eff}}-[\text{Fe/H}]} = 0.87 \) and \( \rho_{\log g-[\text{Fe/H}]} = 0.92 \).

One first thing to note about the performance of ZASPE on the Sun and Arcturus, beyond the fact that the resulting stellar parameters are consistent with known values produced by current state of the art analyses, is the magnitude of the uncertainties. Despite the very high signal-to-noise ratio of the spectra, the estimated uncertainties in \( T_{\text{eff}} \) are \( \sim 50 \text{ K} \). This compares very well with the uncertainty of \( \sigma_{T_{\text{eff}}} = 59 \text{ K} \) that Torres et al. (2012) adds in quadrature to their formal uncertainties. This uncertainty is obtained from the overall scatter of their measurements for stars with multiple determinations obtained with different methods (SPC, SME and/or MOOG). In
Figure 3.5: Results obtained by ZASPE for the Sun. The left panels show the distribution of possible sets of atmospheric parameters obtained from the random sampling method. Strong correlations between the parameters are found. The blue circles correspond to the parameters of the synthetic spectrum that produce the best match, while the red circles are reference values from the literature. The right panels correspond to the marginalised distributions of outcomes for each atmospheric parameter. Blue lines show the parameters of the synthetic spectrum that produce the best match, while red lines are the reference values. The errors reported by ZASPE correspond to the standard deviations of these distributions.
Figure 3.6: Same as Figure 3.5 but for Arcturus.
the same vein, the uncertainties in [Fe/H] for the Sun\textsuperscript{3} are of order $\sim 0.05$ dex, compared with the value of $\sigma_{[Fe/H]} = 0.062$ adopted by Torres et al. (2012). From this exercise we can see that the uncertainties returned by ZASPE are a realistic reflection of the model uncertainties that dominate in our case. As opposed to the methods based on repeated measurements on a sample of objects, ZASPE can provide that uncertainty on a per spectrum basis, and also provides the correlation with other parameters.

In order to explore how the magnitude of the computed errors depend on the atmospheric parameters, we analysed the results that were obtained by ZASPE on the dataset presented in Section 3.2.6, where we obtained the atmospheric parameters and their associated errors for a set of FEROS spectra of stars that have been already analysed by SWEET-Cat. From this sample we conclude that there is no strong dependence between the magnitude of the errors that we estimate and the atmospheric parameters of the star. However, there are two tentative trends that are shown in Figure 3.7. The top panel of the figure shows that dwarf stars tend to have lower errors in log $g$ than giant stars. The origin of this correlation can be associated with the tight pressure sensitivity of the shape of the wings of strong absorption lines, which is only present in dwarf stars. In the case of giant stars the principal factor that produces variation in log $g$ are subtle changes in the depth of shallow lines generated from variations in the continuum absorption. The bottom panel of Figure 3.7 shows that for dwarf stars, the $T_{\text{eff}}$ errors computed by ZASPE tend to be higher or at least have a larger dispersion for hotter stars, which can arise from the higher rotational velocity F-type stars have in comparison to G-type stars, but also because at higher temperatures ($T_{\text{eff}} > 6000$ K), a large fraction of the elements in the atmosphere start to get ionised and therefore there are less available absorption lines. However, the reported trends of both panels show important levels of scatter. In particular there is a cluster

\textsuperscript{3}The [Fe/H] uncertainty for Arcturus is higher by a factor of $\approx 2$. This is a consequence of the less constrained value of log $g$ for a giant, which has an impact on the uncertainty of [Fe/H].
Figure 3.7: Top: errors in log g reported by ZASPE as function of the log g values. Dwarfs stars have in general smaller errors than giant stars. Bottom: errors in $T_{\text{eff}}$ reported by ZASPE as function of the $T_{\text{eff}}$ values. In the case of dwarf stars, hotter stars tend to have larger errors.

of stars with $T_{\text{eff}} \approx 5000$ K, log g $\approx 3.5$ dex and similar [Fe/H] values that shows a large scatter in the magnitude of their errors. The source of this dispersion may be associated to other systematic effects, like differences in particular abundances or incorrect assumptions in the micro- and macro-turbulence values.

As a further example of the performance of ZASPE, we analysed an archival Keck/HIRES (Vogt et al. 1994) spectrum of WASP-14. We chose this star as it is representative of the use of atmospheric parameter estimation in the process of discovery and characterization of exoplanets, which was the main motivation for developing ZASPE. Additionally, WASP-14 was analysed
with Starfish by Czekala et al. (2014). As Starfish is the only other approach we are aware of that attempts to properly take into account the model uncertainties as we do in this work, it offers a very interesting point of comparison. Czekala et al. (2014) estimate the stellar parameters of WASP-14 using a spectrum from the TRES spectrograph on the Fred Lawrence Whipple Observatory 1.5 m telescope and fixing log $g$ to the value obtained by Torres et al. (2012) by fitting the transit light-curve, namely log $g = 4.29$. They estimate parameters using both Kurucz and PHOENIX stellar atmospheric models. The Starfish estimates and their uncertainties are presented in their Table 1 and are (values using Kurucz models) $T_{\text{eff}} = 6426 \pm 21$ K, $[\text{Fe/H}] = -0.26 \pm 0.01$ and $v \sin i = 4.47 \pm 0.06$ km s$^{-1}$.

Running ZASPE on the Keck/HIRES spectrum with fixed log $g = 4.29$ results in the following estimates: $T_{\text{eff}} = 6515 \pm 64$ K, $[\text{Fe/H}] = -0.15 \pm 0.04$ and $v \sin i = 5.55 \pm 0.37$ km s$^{-1}$. Again, the uncertainties are reasonable based on what is expected from studies that have obtained measurements with different methods such as Torres et al. (2012), and are actually made somewhat artificially low by fully fixing log $g$\footnote{The stellar parameters obtained leaving log $g$ free are: $T_{\text{eff}} = 6501 \pm 134$ K, $[\text{Fe/H}] = -0.17 \pm 0.07$, $v \sin i = 5.58 \pm 0.5$ km s$^{-1}$ and log $g = 4.22 \pm 0.18$.}. The difference with the uncertainties obtained by Starfish are substantial, with the Starfish uncertainties being underestimated based on the experience provided by studies such as that of Torres et al. (2012). This is also clear from comparing the parameters derived by Starfish on the same data using different stellar models, as they are in some cases formally inconsistent given their error bars, something that should not be the case if the uncertainties arising from model imperfections have been properly estimated. Figure 3.8 shows a portion of the HIRES spectrum of WASP-14 and the synthetic spectrum with the optimal parameters derived by ZASPE. The sensitive zones determined by ZASPE are shaded blue.

It is worthwhile trying to understand why the approach of Czekala et al. (2014) leads to under-
estimated uncertainties. Their approach is very principled, and being immersed in a likelihood, it is very appealing for inference. Their approach takes into account the mismatches between models and data through modelling the variance structure with a Gaussian process. To that effect, a mixture of non-stationary kernels that indicate regions of very strong deviation, and a stationary global kernel, are used. The non-stationary kernels, with large variances, have the effect of ignoring regions where those kernels are instantiated, and is a way of eliminating lines that are outliers in a principled way. The stationary kernel accounts for the typical mismatch between the model and the data, and it is chosen to be of the form of a Matérn $\nu = 3/2$ kernel, tapered by a Hann window function to keep the global covariance matrix sparse. In this approach, the possible mismatches between the model and the data are given by the space of functions generated by the Matérn $\nu = 3/2$ kernel with the hyperparameter distributions learned in the inference process.

The key observation is that the mismatches are not appropriately described by a stationary kernel, as they ought to exist mostly around the lines, and thus the process that would be needed to
account for the mismatch structure is fundamentally non-stationary. In our re-sampling scheme, we just modify the depth of the lines, exploring thus systematically variations in the models that have physical plausibility. Variations given by a stationary Gaussian kernel will have no correlation with the line structure, and would be therefore mostly unphysical. This can be seen in the right panels of Figure 4 in Czekala et al. (2014): the random draws from the stationary kernel have structure on locations that are uncorrelated with the spectral lines. The stationary kernel encapsulates the typical covariance structure of the mismatch, including large swaths of the spectrum that are continuum where little mismatch is observed, as those regions are less sensitive to the parameters. One expects then that the amplitude of the variance is a sort of average description of continuum and line regions, and would thus underestimate the variance at the more relevant regions of the spectral lines. In summary, we believe the inability of Starfish to deliver realistic uncertainties is due to fact that their use of a Matérn $\nu = 3/2$ kernel is not necessarily expected to correctly describe the functional space of mismatches and the variance amplitude relevant at the location of spectral lines.

3.4 Summary

In this work, we have presented a new algorithm based on the spectral synthesis technique for estimating stellar atmospheric parameters of FGK-type stars from high resolution echelle spectra. The comparison between the data and the models is performed iteratively in the most sensitive zones of the spectra to changes in the atmospheric parameters. These zones are determined after each ZASPE iteration and the regions of the spectra that strongly deviate from the best model are not considered in future iterations.

ZASPE computes the errors and correlations in the parameters from the data itself by assuming
that the uncertainties are dominated by the systematic mismatches between the data and the models that arise from unknown parameters of the particular atomic transitions. These systematic effects manifest themselves by randomly modifying the strength of the absorption lines of the synthesised spectra. The distribution of mismatches is determined by ZASPE from the observed spectra and the synthetic model that produces the best fit. A random sampling method uses an empirical distribution of line strength mismatches to modify the complete grid of synthetic spectra in a number of realisations and a new set of stellar parameters is determined in each realisation. The complete covariance matrix can be computed from the distribution of outputs of the random sampling method.

We have validated ZASPE by comparing its estimates with the SWEET-Cat catalogue of stellar parameters. We have found that the synthetic libraries of Coelho et al. (2005) and Husser et al. (2013) are not suitable for obtaining reliable atmospheric parameters because they present some strong systematic trends when comparing ZASPE results obtained with these grids against SWEET-Cat reference values. We have detailed the methodology to generate our own library of synthetic spectra that we have shown is able to obtain consistent results with the SWEET-Cat catalogue. We have estimated stellar parameters for the Sun and Arcturus using high signal-to-noise archival spectra, obtaining results consistent with state-of-the art estimates for these archetypical stars. Importantly, we obtain uncertainties that are in line with the expected level of systematic uncertainties based on studies that have analysed spectra of a sample of stars with different methods. Finally, we have estimated parameters for the star WASP-14, as both a way to gauge performance on a typical star that is followed-up in exoplanetary transit surveys and to compare to the Starfish code, the only other approach that we are aware of that deals with the systematic mismatch between models and data. Unlike ZASPE the Starfish code delivers underestimated uncertainties, a fact we believe is due to the modelling of the mismatch structure using a stationary kernel for what is fundamentally a non-stationary process as it is concentrated
in the line structure.

Currently ZASPE works for stars of spectral type FGK. The main barriers to extend the use of ZASPE for stars with lower $T_{\text{eff}}$ are related to the assumption that the systematic mismatches can be modelled by one random variable that modifies the strength of the absorption lines. Molecular bands become the principal feature in the spectra for stars with $T_{\text{eff}} < 4000$ K and a more complex model is required to characterise the systematic differences between observed and synthetic spectra. Extension to later types will be the subject of future efforts.

ZASPE is mostly a Python based code with some routines written in C. It has the option of being run in parallel with the user having the capability of entering the number of cores to be utilised. On a 16 core CPU it takes $\approx 10$ minutes for ZASPE to find the synthetic spectrum that produces the best match with the data. However, to determine the covariance matrix a couple of hours are required. ZASPE has been recently adopted as the standard procedure for estimating the stellar atmospheric parameters of the transiting extrasolar systems discovered by the HATSouth survey (Bakos et al. 2013); to date its results have been used for the analysis of HATS-9, HATS-10, HATS-13, HATS-14, HATS-15, HATS-16 and HATS-17 (Brahm et al. 2015b; Mancini et al. 2015; Ciceri et al. 2015a; Brahm et al. 2015a). ZASPE is made publicly available at github.com/rabrahm/zaspe.
Chapter 4

HATS-9b and HATS-10b: Two compact hot Jupiters in field 7 of the K2 mission

Abstract

We report the discovery of two transiting extrasolar planets by the HATSouth survey. HATS-9b orbits an old (10.8 ± 1.5 Gyr) V=13.3 G dwarf star, with a period $P \approx 1.9153$ d. The host star has a mass of $1.03 M_\odot$, radius of $1.503 R_\odot$ and effective temperature $5366 \pm 70$ K. The planetary companion has a mass of $0.837 M_J$, and radius of $1.065 R_J$ yielding a mean density of $0.85 \text{ g cm}^{-3}$. HATS-10b orbits a V=13.1 G dwarf star, with a period $P \approx 3.3128$ d. The host star has a mass of $1.1 M_\odot$, radius of $1.11 R_\odot$ and effective temperature $5880 \pm 120$ K. The planetary companion has a mass of $0.53 M_J$, and radius of $0.97 R_J$ yielding a mean density of $0.7 \text{ g cm}^{-3}$. Both planets are compact in comparison with planets receiving similar irradiation from their host stars, and lie in the nominal coordinates of Field 7 of K2 but only HATS-9b

falls on working silicon. Future characterization of HATS-9b with the exquisite photometric precision of the Kepler telescope may provide measurements of its reflected light signature.

4.1 Introduction

Our current understanding of the structure and orbital evolution of extrasolar giant planets has been, to a large degree, informed by the characterization of transiting planetary systems. Besides the determination of the planet radius, true mass, and bulk density, follow-up studies of transiting extrasolar planets (TEPs) allow the extraction of valuable information, like the spin-orbit angle and the properties and composition of the planetary atmospheres, that are not be easily recovered unless the orbital plane is favorably oriented such that the planet eclipses its host star.

Detections of giant TEPs, mostly driven by transiting ground based surveys like SuperWASP (Pollacco et al. 2006) and HATNet (Bakos et al. 2004), have revealed a large number of systems in the region of parameter space with $R_p > 0.8R_J$, $M_p > 0.4M_J$, $P < 5$ d and FGK-type host stars. The measured properties of these systems, coupled with subsequent follow-up studies, have been fundamental for testing formation and interior models of these giant planets, which are known as hot Jupiters.

New ground-based transiting surveys like HATSouth (Bakos et al. 2013) have been designed with the goal of expanding the parameter space of well characterized TEPs by detecting planets with smaller radii ($R_p < 0.4R_J$) and/or longer periods ($P > 10$ days). In the process of searching for these kinds of planets, new hot Jupiters are detected which contribute to enlarging the sample of known systems. Even though many hot Jupiters are already known, more are still needed to make headway into understanding their physical properties, e.g. a firm understanding of the mechanism that causes some hot Jupiters to have inflated radii (e.g. HAT-P-32b and HAT-P-
New planet discoveries around bright stars, accessible by follow-up facilities, are especially valuable given the wealth of detailed studies that they can be subject to. Indeed, some of the most analyzed and characterized giant TEPs are three planets (TrES-2b, HAT-P-7b and HAT-P-11b) that were detected by ground-based surveys (Pál et al. 2008; Bakos et al. 2010; O'Donovan et al. 2006) and later observed by NASA's Kepler mission (Borucki et al. 2010). Even though the primary goal of the Kepler satellite was the detection of planets near the habitable zone for estimating their frequency and distribution in our galaxy, the high photometric precision of Kepler allowed very detailed studies of the small population of giant planets on close orbits around moderately bright stars (V < 14) that fell in its field of view.

Kepler was able to detect secondary transits and phase variations on TrES-2b and HAT-P-7b (Esteves et al. 2013) which were useful in the study of their atmospherical properties, such as the determination of the geometric albedos and planetary phase curve offsets. Doppler beaming and ellipsoidal variations measured with Kepler also constrained the mass of those planets. In the case of HAT-P-11b, Kepler observations were useful in characterizing the activity of the K-type host star; and the analysis of crossing stellar spots allowed the determination of the spin-orbit misalignment of this system (Deming et al. 2011; Sanchis-Ojeda & Winn 2011). Simultaneous observations of the transits of HAT-P-11b by Kepler and Spitzer allowed also the detection of water vapor in the atmosphere of this Neptune-size planet (Fraine et al. 2014). Estimation of the planetary physical parameters depend strongly on the estimated stellar properties. In this regard, Kepler was also able to measure model independent stellar properties by the use of asteroseismology on the three mentioned systems (Christensen-Dalsgaard et al. 2010).

After the failure of two of its reaction wheels, the Kepler satellite is still working, but with a new observation strategy and a photometric precision within a factor of ~2 of the nominal
Kepler mission performance (e.g., Vanderburg & Johnson 2014; Aigrain et al. 2015; Foreman-Mackey et al. 2015; Crossfield et al. 2015). This new mission concept, called K2 (Howell et al. 2014), will observe 10 fields, each for a period of approximately 70 days, and some of these fields lie in the southern hemisphere. One of the limitations of K2 is that the number of stars that can be monitored in each field is substantially lower than for the original Kepler mission. For this reason, the pre-selection of targets, based on ground-based observations of K2 fields is especially important for an efficient use of the satellite.

In this work we present the discovery of HATS-9b and HATS-10b, two hot Jupiters discovered by the HATSouth survey which are located in the nominal coordinates of Field 7 of K2 mission. In Section 4.2 we summarize the observations that allowed the discovery and confirmation of these planets. In Section 4.3 we show the global analysis of the spectroscopic and photometric data that confirmed the planetary nature of the transiting candidates and also rejected blend scenarios that can mimic the photometric and radial velocity signals. Our findings are discussed in Section 4.4.

4.2 Observations

4.2.1 Photometric detection

HATS-9 and HATS-10 were identified as transiting planetary host candidates after obtaining ~10000 images of the same field with three stations on the three HATSouth observing sites. The number of photometric observations that were taken for each star on each of the HATSouth stations is indicated in Table 4.1, where it can be seen that in both cases ~45% of the observations came from the HATSouth station located at Las Campanas Observatory (LCO).
The HATSouth observations consist of four-minute Sloan $r$-band exposures obtained with 24 Takahashi E180 astrographs (18cm aperture) coupled to Apogee 4Kx4K U16M ALTA CCDs. Readout times are of the order of one minute which results in a cadence of about 5 minutes. Detailed descriptions of the image processing steps and the candidate identification procedures of HATSouth data can be found in Bakos et al. (2013) and Penev et al. (2013). Briefly, after applying aperture photometry on the images, the light curves generated are detrended using external parameter decorrelation (EPD) and trend filtering algorithm (TFA Kovács et al. 2005). Periodic transits on the detrended light curves are then searched using Box-fitted Least Squares (BLS) algorithm (Kovács et al. 2002).

Figure 4.1 shows the phase-folded detection light curves of HATS-9b and HATS-10b, where a clear $\sim 10$ mmag flat-bottom transit can be observed in both cases.

Figure 4.1: Phase-folded unbinned HATSouth light curves for HATS-9 (left) and HATS-10 (right). In each case we show two panels. The top panel shows the full light curve, while the bottom panel shows the light curve zoomed-in on the transit. The solid lines show the model fits to the light curves. The dark filled circles in the bottom panels show the light curves binned in phase with a bin size of 0.002.
Table 4.1: Summary of photometric observations

<table>
<thead>
<tr>
<th>Instrument/Field&lt;sup&gt;a&lt;/sup&gt;</th>
<th>Date(s)</th>
<th># Images</th>
<th>Cadence&lt;sup&gt;b&lt;/sup&gt; (sec)</th>
<th>Filter</th>
<th>Precision&lt;sup&gt;c&lt;/sup&gt; (mmag)</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>HATS-9</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>HS-1/G579</td>
<td>2010 Mar-2011 Aug</td>
<td>4317</td>
<td>300</td>
<td>r band</td>
<td>6.9</td>
</tr>
<tr>
<td>HS-3/G579</td>
<td>2010 Mar-2011 Aug</td>
<td>2138</td>
<td>303</td>
<td>r band</td>
<td>7.6</td>
</tr>
<tr>
<td>HS-5/G579</td>
<td>2010 Sep-2011 Aug</td>
<td>2784</td>
<td>303</td>
<td>r band</td>
<td>6.9</td>
</tr>
<tr>
<td>FTS</td>
<td>2013 Apr 11</td>
<td>134</td>
<td>80</td>
<td>i band</td>
<td>1.4</td>
</tr>
<tr>
<td>PEST</td>
<td>2013 May 31</td>
<td>186</td>
<td>130</td>
<td>R&lt;sub&gt;C&lt;/sub&gt; band</td>
<td>3.4</td>
</tr>
<tr>
<td><strong>HATS-10</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>HS-1/G579</td>
<td>2009 Sep-2011 Aug</td>
<td>4389</td>
<td>301</td>
<td>r band</td>
<td>7.3</td>
</tr>
<tr>
<td>HS-3/G579</td>
<td>2010 Mar-2011 Aug</td>
<td>2596</td>
<td>303</td>
<td>r band</td>
<td>7.2</td>
</tr>
<tr>
<td>HS-5/G579</td>
<td>2011 Mar-2011 Aug</td>
<td>3297</td>
<td>303</td>
<td>r band</td>
<td>7.8</td>
</tr>
<tr>
<td>CTIO 0.9m</td>
<td>2012 Aug 29</td>
<td>69</td>
<td>213</td>
<td>z band</td>
<td>2.3</td>
</tr>
<tr>
<td>FTS</td>
<td>2013 Apr 05</td>
<td>142</td>
<td>63</td>
<td>i band</td>
<td>4.3</td>
</tr>
<tr>
<td>GROND</td>
<td>2013 Jun 14</td>
<td>92</td>
<td>156</td>
<td>g band</td>
<td>0.8</td>
</tr>
<tr>
<td>GROND</td>
<td>2013 Jun 14</td>
<td>88</td>
<td>156</td>
<td>r band</td>
<td>1.3</td>
</tr>
<tr>
<td>GROND</td>
<td>2013 Jun 14</td>
<td>94</td>
<td>156</td>
<td>i band</td>
<td>0.7</td>
</tr>
<tr>
<td>GROND</td>
<td>2013 Jun 14</td>
<td>89</td>
<td>156</td>
<td>z band</td>
<td>0.8</td>
</tr>
<tr>
<td>PEST</td>
<td>2013 Jun 27</td>
<td>145</td>
<td>130</td>
<td>R&lt;sub&gt;C&lt;/sub&gt; band</td>
<td>4.6</td>
</tr>
</tbody>
</table>

<sup>a</sup> For HATSouth data we list the HATSouth unit and field name from which the observations are taken. HS-1 and -2 are located at Las Campanas Observatory in Chile, HS-3 and -4 are located at the H.E.S.S. site in Namibia, and HS-5 and -6 are located at Siding Spring Observatory in Australia. Each field corresponds to one of 838 fixed pointings used to cover the full 4π celestial sphere. All data from a given HATSouth field are reduced together, while detrending through External Parameter Decorrelation (EPD) is done independently for each unique field+unit combination.

<sup>b</sup> The median time between consecutive images rounded to the nearest second. Due to weather, the day–night cycle, guiding and focus corrections, and other factors, the cadence is only approximately uniform over short timescales.

<sup>c</sup> The RMS of the residuals from the best-fit model.
4.2.2 Spectroscopic Observations

Transit-like light curves can be produced by different configurations of stellar binaries. Spectroscopic observations are required to reject false positives and to obtain the orbital parameters and masses of the true planets. Due to the great number of HATSouth candidates and the limited available observing time on spectroscopic facilities, this follow-up is performed in a two-step procedure as we now describe. All spectroscopic observations are summarized in Table 4.2.

First, initial spectra are acquired (with either low resolution, or low S/N) to make a rough estimation of the stellar parameters, identifying spectra composed of more than one star, and measuring RV variations produced by stellar mass companions. HATS-9 was observed with WIFeS (Dopita et al. 2007) on the ANU 2.3m telescope, obtaining $T_{\text{eff}} = 5821 \pm 300$ K, $\log g = 3.9 \pm 0.3$, $[\text{Fe/H}] = 0.5 \pm 0.5$; and with ARCES on the APO 3.5m obtaining $T_{\text{eff}} = 5692 \pm 50$ K, $\log g = 4.14 \pm 0.1$, $[\text{Fe/H}] = 0.50 \pm 0.08$. Both estimates of stellar parameters were consistent with a G-type dwarf, but the sub-solar surface gravity value points towards a slightly evolved system. Details on the observing strategy, reduction methods and the processing of the spectra for WIFeS can be found in Bayliss et al. (2013). The ARCES observation was carried out using the $1'6 \times 3'2$ slit yielding an echelle spectrum with 107 orders covering the wavelength range 3200–10000Å at a resolution of $\Delta \lambda / \lambda \sim 31500$. A single ThAr lamp spectrum was obtained immediately following the science exposure with the telescope still pointed toward HATS-9. The science observation was reduced to a wavelength-calibrated spectrum using the standard IRAF echelle package\(^1\), and analyzed using the Spectral Parameter Classification (SPC) program (Buchhave et al. 2012) to determine the radial velocity and stellar atmospheric parameters.

Reconnaissance spectroscopy was performed for HATS-10 using the echelle spectrograph mounted

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\(^1\)IRAF is distributed by the National Optical Astronomy Observatories, which are operated by the Association of Universities for Research in Astronomy, Inc., under cooperative agreement with the National Science Foundation.
on the du Pont 2.5m telescope at Las Campanas Observatory. One observation using the 1" × 4" slit (Δλ/λ ~ 40000) was enough to confirm that HATS-10 has a single lined spectrum with the following stellar parameters: $T_{\text{eff}} = 6100 \pm 100$ K, $\log g = 4.6 \pm 0.5$, $[\text{Fe/H}] = 0.0 \pm 0.5$, $v \sin i = 5.0 \pm 2.0$ km/s. This spectrum was reduced and analysed with CERES (see Chapter 2).

Once both candidates were identified as single-lined late-type dwarfs, spectra from high precision instruments were required to measure RV variations with high precision (< 30 m/s) in order to measure the mass of the substellar companions and obtain the orbital parameters. HATS-9 and HATS-10 were observed several times with Coralie (Queloz et al. 2001) on the 1.2m Euler telescope, FEROS (Kaufer & Pasquini 1998) on the 2.2m MPG telescope, and HDS on the 8m Subaru telescope (Noguchi et al. 2002). Coralie and FEROS data were processed with the pipeline described in Jordán et al. (2014), where RV values are obtained using the cross correlation technique against a binary mask and bisector span (BS) measurements are computed from the cross-correlation peak following Queloz et al. (2001). HDS RVs were measured using the procedure detailed in Sato et al. (2002) which are in turn based on the method of Butler et al. (1996) while BS values were obtained following Bakos et al. (2007).

Phased high-precision RV and BS measurements are shown for each system in Figure 4.2 and the data are listed in Tables 4.3 and 4.4. Both candidates show RV variations in phase with photometric ephemeris, however for HATS-10 the residuals are higher than expected. This deviation can be partly explained by moonlight contamination in 5 spectra acquired with Coralie in August 2013 which are marked with crosses in Figure 4.2. There are no significant correlations between RV and BS variations and thus we conclude the RV variations are not produced by stellar activity. The 95% confidence interval for the Pearson correlation coefficient between RV and BS was computed for both candidates using a bootstrap procedure. The confidence intervals are [-0.57, 0.07] and [-0.43, 0.37] for HATS-9 and HATS-10, respectively. The individual
FEROS spectra were median combined for both candidates to perform a precise estimation of the stellar parameters.

Table 4.2: Summary of spectroscopy observations

<table>
<thead>
<tr>
<th>Instrument</th>
<th>UT Date(s)</th>
<th># Spec.</th>
<th>Res. $\Delta \lambda / \lambda$</th>
<th>S/N</th>
<th>Range$^a$</th>
<th>$\gamma_{RV}^b$ (km s$^{-1}$)</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>HATS-9</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>APO 3.5m/ARCES</td>
<td>2012 Aug 25</td>
<td>1</td>
<td>31.5</td>
<td>27</td>
<td>-11.5</td>
<td></td>
</tr>
<tr>
<td>ANU 2.3m/WIFES</td>
<td>2012 Sep 8</td>
<td>1</td>
<td>3</td>
<td>140</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Euler 1.2m/Coralie</td>
<td>2012 Nov 6-10</td>
<td>4</td>
<td>60</td>
<td>14-20</td>
<td>-10.634</td>
<td></td>
</tr>
<tr>
<td>MPG 2.2m/FEROS</td>
<td>2012 Aug-2013 May</td>
<td>9</td>
<td>48</td>
<td>32-76</td>
<td>-10.653</td>
<td></td>
</tr>
<tr>
<td>Subaru 8m/HDS</td>
<td>2012 Sep 19</td>
<td>3</td>
<td>60</td>
<td>100-114</td>
<td>...</td>
<td></td>
</tr>
<tr>
<td>Subaru 8m/HDS + I$_2$</td>
<td>2012 Sep 20-22</td>
<td>9</td>
<td>60</td>
<td>60-100</td>
<td>...</td>
<td></td>
</tr>
<tr>
<td><strong>HATS-10</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>du Pont 2.5m/Echelle</td>
<td>2013 Aug 21</td>
<td>1</td>
<td>40</td>
<td>48</td>
<td>-29.2</td>
<td></td>
</tr>
<tr>
<td>Euler 1.2m/Coralie</td>
<td>2012 Aug - 2013 Aug</td>
<td>12</td>
<td>60</td>
<td>17-23</td>
<td>-28.131</td>
<td></td>
</tr>
<tr>
<td>MPG 2.2m/FEROS</td>
<td>2013 Mar-Jul</td>
<td>5</td>
<td>48</td>
<td>29-85</td>
<td>-28.044</td>
<td></td>
</tr>
<tr>
<td>Subaru 8m/HDS</td>
<td>2012 Sep 22</td>
<td>3</td>
<td>60</td>
<td>74-94</td>
<td>...</td>
<td></td>
</tr>
<tr>
<td>Subaru 8m/HDS + I$_2$</td>
<td>2012 Sep 19-21</td>
<td>9</td>
<td>60</td>
<td>41-99</td>
<td>...</td>
<td></td>
</tr>
</tbody>
</table>

$^a$ S/N per resolution element near 5180 Å.

$^b$ For Coralie and FEROS this is the systemic RV from fitting an orbit to the observations in Section 4.3.3. For ARCES and the du Pont Echelle it is the measured RV of the single observation. We do not provide this quantity for instruments for which only relative RVs are measured, or for WiFeS which was only used to measure stellar atmospheric parameters.

### 4.2.3 Photometric follow-up observations

In order to confirm the occurrence of the transits and to better constrain the orbital and physical parameters of the companions, higher precision light curves for both candidates were acquired using several telescopes around the globe. Table 4.1 summarizes the key aspects of this photometric follow-up, including the dates of the observations, the cadence and the filter.

Two partial transits of HATS-9 were detected using the 0.3m Perth Exoplanet Survey Telescope
Figure 4.2: Phased high-precision RV measurements for HATS-9 (left), and HATS-10 (right) from HDS (filled circles), FEROS (open triangles), and Coralie (filled triangles). In each case we show three panels. The top panel shows the phased measurements together with our best-fit model (see Table 4.7) for each system. Zero-phase corresponds to the time of mid-transit. The center-of-mass velocity has been subtracted. The second panel shows the velocity $O-C$ residuals from the best fit. The error bars include the jitter terms listed in Table 4.7 added in quadrature to the formal errors for each instrument. The third panel shows the bisector spans (BS), with the mean value subtracted. Note the different vertical scales of the panels. RV measurements highly contaminated with moonlight are marked with crosses.

(PEST) and the Spectral camera on the 2m Faulkes Telescope South (FTS), part of Las Cumbres Observatory Global Telescope (LCOGT). Results of these observations are presented in Table 4.5 and shown in Figure 4.3. Two partial transits of HATS-10 were observed with FTS and the CTIO 0.9m telescope. Another two full transits were measured with PEST and the GROND instrument on the MPG 2.2 m. These HATS-10 light curves are shown in Figure 4.4. All the facilities used for high precision photometric follow-up have been previously used by HATSouth; the instrument specifications, observation strategies and reduction procedures adopted can be
Figure 4.3: Left: Unbinned transit light curves for HATS-9. The light curves have been corrected for quadratic trends in time fitted simultaneously with the transit model. The dates of the events, filters and instruments used are indicated. The second curve is displaced vertically for clarity. Our best fit from the global modeling described in Section 4.3.3 is shown by the solid lines. Right: residuals from the fits are displayed in the same order as the left curves. The error bars represent the photon and background shot noise, plus the readout noise.

found in Bayliss et al. (2013), Zhou et al. (2014b), Hartman et al. (2015b) and Mohler-Fischer et al. (2013) for FTS, PEST, CTIO 0.9m, and GROND, respectively.

4.3 Analysis

4.3.1 Properties of the parent star

We determine precise stellar parameters for HATS-9 and HATS-10 using the ZASPE code (see Chapter 3) on median combined FEROS spectra. The resulting parameters for HATS-9 are: $T_{\text{eff}} = 5363 \pm 90$ K, $\log{g} = 3.97 \pm 0.2$, $[\text{Fe/H}] = +0.33 \pm 0.09$, $v \sin{i} = 4.67 \pm 0.50$ km/s; while for
Figure 4.4: Similar to Figure 4.3; here we show the follow-up light curves for HATS-10.

HATS-10 we get: $T_{\text{eff}}=5974 \pm 110$ K, $\log g = 4.44 \pm 0.13$, $[\text{Fe/H}]=+0.19 \pm 0.07$, $v \sin i=5.66 \pm 0.50$ km/s.

These sets of stellar parameters were refined using the information contained in the transit
light-curves. The stellar mean density ($\rho_*$) can be computed directly from one of the light-curve model parameters ($a/R_*$) and the period and eccentricity of the orbit by using Kepler’s third law with only a slight dependence on the stellar parameters through the limb-darkening coefficients (Sozzetti et al. 2007). The spectroscopically determined $T_{\text{eff}_*}$ and $[Fe/H]$ were coupled with $\rho_*$ and Yonsei-Yale stellar evolution models (YY; Yi et al. 2001) to determine the stellar physical parameters ($R_*$, $M_*$ and the age of the star), which were used to compute a new and more precise estimation of $\log g_*$ for HATS-9 ($\log g_*=4.12 \pm 0.04$) and HATS-10 ($\log g_*=4.38 \pm 0.03$). A new set of $T_{\text{eff}_*}$, $[Fe/H]$, $v\sin i$ was determined using ZASPE with $\log g_*$ fixed to the precise values obtained by modeling the light curves, followed by a new estimation of $\rho_*$ and a new modeling of stellar isochrones. The new set of stellar parameters fixing $\log g_*$, which are the ones we adopted for further analysis, were consistent with the initial values quoted in the previous paragraph and are listed in Table 4.6, where distances are determined by comparing the measured broad-band photometry listed in that table to the predicted magnitudes in each filter from the isochrones. We assume a $R_V = 3.1$ extinction law from Cardelli et al. (1989) to determine the extinction. The $1\sigma$ and $2\sigma$ confidence ellipsoids in $T_{\text{eff}_*}$ and $\rho_*$ are plotted in Figure 4.5 for both planet hosts, along with the YY isochrones for the ZASPE determined $[Fe/H]$. We find that HATS-9 is a $1.030 \pm 0.039 M_\odot$, $1.503^{+0.101}_{-0.043} R_\odot$, quite evolved (10.8 ± 1.5 Gyr) star, while HATS-10 is a $1.101 \pm 0.054 M_\odot$, $1.105^{+0.055}_{-0.040} R_\odot$ main-sequence star.

We attempted to measure the lithium absorption line at 6707.8 Å for testing the age estimation of HATS-9 but the quality of our spectra was only enough to rule out a strong absorption feature.

4.3.2 Excluding blend scenarios

In order to exclude blend scenarios we carried out a blend analysis of the observations following Hartman et al. (2012). For HATS-9 we find that scenarios involving blends between a stellar
Figure 4.5: Model isochrones from Yi et al. (2001) for the measured metallicities of HATS-9 (left) and HATS-10 (right). In each case we show models for ages of 0.2 Gyr and 1.0 to 14.0 Gyr in 1.0 Gyr increments (ages increasing from left to right). The adopted values of $T_{\text{eff}}$ and $\rho_*$ are shown together with their 1\(\sigma\) and 2\(\sigma\) confidence ellipsoids. The initial values of $T_{\text{eff}}$ and $\rho_*$ from the first ZASPE and light curve analyzes are represented with a triangle.

eclipsing binary and a foreground or background star can be ruled out with greater than 5\(\sigma\) confidence based on the photometric data alone. The primary constraint in this case is the lack of out-of-transit variations seen in the HATSouth light curve. Due to the short orbital period, the best-fit blend model which reproduces the shape of the transit has a $\sim 1$ mmag amplitude ellipsoidal variation, and a $\sim 0.5$ mmag deep secondary eclipse, neither of which are detected in the HATSouth observations. Moreover the Subaru/HDS observations of HATS-9 show no significant bisector span variation (the RMS scatter of the BS measurements is $12 \text{ m s}^{-1}$) providing further evidence that the system is not a blended eclipsing binary. For HATS-10 the photometric observations can be fit by a G+M star eclipsing binary blended with another G star that is slightly brighter than the primary in the eclipsing system. Based on the difference in $\chi^2$, this model is indistinguishable from a single G star with a transiting planet. We simulated spectra for blend models that could plausibly fit the photometric observations, finding that it all cases the blended systems would have easily been detected as having composite spectra. They also would produce RV and BS variations of several $\text{ km s}^{-1}$, whereas the observed RV variation
is $67 \pm 10$ m s$^{-1}$, and the Subaru/HDS BS scatter is only 18 m s$^{-1}$. We conclude that neither HATS-9 nor HATS-10 is a blended eclipsing binary system. As is often the case, however, we are not able to rule out the possibility that either transiting planet system has a fainter stellar-mass companion. For both systems a stellar companion of any mass, up to the mass of the planet-hosting star, is possible. If a massive stellar companion is present in a given system, the true planet radius would be up to $\sim 60\%$ larger than inferred here. The planet mass would also be larger. High resolution adaptive optics imaging, and/or long-term RV observations are needed to determine whether either system has a stellar companion (e.g. Howell et al. 2011; Horch et al. 2014; Everett et al. 2015).

4.3.3 Global modeling of the data

We modeled the HATSouth photometry, the follow-up photometry, and the high-precision RV measurements following Pál et al. (2008), Bakos et al. (2010), and Hartman et al. (2012). We fit Mandel & Agol (2002) transit models to the light curves, allowing for a dilution of the HATSouth transit depth as a result of blending from neighboring stars and over-correction by the trend-filtering method. For the follow-up light curves we include a quadratic trend in time in our model for each event to correct for systematic errors in the photometry. We fit Keplerian orbits to the RV curves allowing the zero-point for each instrument to vary independently in the fit, and allowing for RV jitter which we also vary as a free parameter for each instrument.

We used a Differential Evolution Markov Chain Monte Carlo procedure (ter Braak 2006; Eastman et al. 2013) to explore the fitness landscape and to determine the posterior distribution of the parameters.

The resulting parameters for each system are listed in Table 4.7. HATS-9b has a radius of 1.065
± 0.098 $R_J$ and a mass of $0.837 \pm 0.029 \ M_J$, while HATS-10b has a radius of $0.969^{+0.061}_{-0.045} \ R_J$
and a mass of $0.526 \pm 0.081 \ M_J$. Both planets have bulk densities slightly lower than the one
of Jupiter ($0.85 \pm 0.19 \ g \ cm^{-3}$ and $0.70 \pm 0.15 \ g \ cm^{-3}$, respectively).

4.4 Discussion

We have presented the discovery of two new transiting planets which are shown on mass-radius
and equilibrium temperature versus radius diagrams in Figure 4.6. From the mass-radius dia-
gram, HATS-9b and HATS-10b can be classified as typical non-inflated hot Jupiters. HATS-9b
is slightly less massive than Jupiter (0.84 $M_J$) and has almost the same radius. Its orbital pe-
riod of $P = 1.9$ days is rather short compared to the period distribution of known hot Jupiters.
HATS-10b has a mass in the range between Saturn and Jupiter (0.53 $M_J$), a radius consistent
with that of Jupiter and a period of $P = 3.3$ days, which is close to the mean period of known
hot Jupiters.

The equilibrium temperature versus radius diagram shows that both planets tend to depart from
the known correlation between the planet radius and its degree of irradiation. This correlation,
first proposed in Guillot (2005), indicates that the inflated radius of some hot Jupiters can be at
least partially explained by the enhanced insolation from their parent star. HATS-9b has a mod-
erately high equilibrium temperature ($T_{eq}=1823^{+52}_{-35} \ K$) due to the small star-planet separation
coupled to the large stellar radius, while HATS-10b has a more typical equilibrium temperature
for a hot Jupiter ($T_{eq}=1407 \pm 39 K$). According to the empirical relations proposed in Enoch
et al. (2012), which give the radius of a giant planet from its equilibrium temperature and semi-
major axis, HATS-9b and HATS-10b should have radii of $1.36 \ R_J$ and $1.22 \ R_J$, respectively. The
observed radii are $3\sigma$ and $5\sigma$ below these values, which indicates that these planets are very
compact given their irradiation levels and that thus additional variables must be responsible of setting the radii of short period giant planets.

One possible explanation is that HATS-9b and HATS-10b may have significant amounts of heavy elements in their cores. According to the interior models of Fortney et al. (2007), both planets will require a core mass of $\sim 60 \, M_\oplus$ to explain their radii based on their masses, stellar host masses and orbital periods for an age of 4.5 Gyr. This explanation can be further motivated by the relatively high metallicity of their parent stars (0.34±0.05 dex and 0.15±0.1 dex, respectively). Several works (Guillot et al. 2006; Burrows et al. 2007; Enoch et al. 2011, 2012) have proposed a correlation between the inferred core mass of giant planets and the metallicity of the parent star. The principal idea behind the proposed correlation is that a more metal rich proto-planetary disk will be more efficient in creating massive cores following the core-accretion scenario of planetary formation. Even though this process is expected to occur in the formation and migration steps, the final relation between the stellar metallicity and the radius of giant planets is not at all clear and other phenomena can act in the opposite direction. As shown by Burrows et al. (2007), the presence of heavy elements in the atmosphere of young giant planets will increase its opacity, slowing the contraction and making the planetary radius more inflated than expected. Moreover, the validity of the proposed correlation has been put into question by the analysis of Zhou et al. (2014a) who find no significant correlation between $R_p$ and [Fe/H] for the complete sample of detected giant TEPs.

The age of the system may be another important variable, since the radius of giant planets should undergo Kelvin-Helmholtz contraction as they age, controlled by their upper radiative atmosphere (Hubbard 1977). Figure 4.7 presents the mass-radius diagram of transiting hot Jupiters having similar insolation levels to HATS-9b ($1750 \, K < T_{eq} < 1900 \, K$). This figure shows that in general the bloating of the atmosphere of strongly irradiated planets is prevented
for more massive hot Jupiters. This correlation presents some outliers, with HATS-9b the most extreme one. A peculiarity of HATS-9b is the advanced age of the system (~11 Gyr) contrasted with the ages of the rest of the planets in Figure 4.7 (<5 Gyr). Among the complete sample of well characterized hot Jupiters, HATS-9b and CoRoT-17 b (10.7 ± 1.0 Gyr) are the oldest systems known to have an age uncertainty better than 20%. Figure 4.8 shows the radius as a function of age for hot Jupiters with $0.5 \ M_J < M_p < 2 \ M_J$ and orbital period $P < 10$ days having age uncertainties smaller than 40%. Systems older than 3 Gyr exhibit the expected contraction of the envelope through time but most of them are systematically more inflated than expected from theoretical models of structure and evolution. By fitting a straight line through the planets with ages higher than 3 Gyr we obtain an empirical contraction function for hot Jupiters: $R_p = 1.45 - 0.03 \ t$, where $t$ is the age of the system in Gyr. The difference between the theoretical function and the empirical relation decreases with the age of the system and for the case of HATS-9b both functions are consistent with the observed values. The proposed empirical relation between the age of the system and the radius of the planet shown in Figure 4.8 supports the study of Burrows et al. (2007) where for young giant planets the higher opacity produced by heavy elements delays the contraction, while at later ages the higher mean molecular weight dominates and leads to smaller radii. However, in order to perform a precise study of the evolution of the radii of giant extrasolar planets, particular models with the properties of each system should be constructed.

A possible confusing factor in Figures 4.6, 4.7 and 4.8 is the assumption of zero albedo and complete heat redistribution. The measurement of secondary transits on these systems in different wavelengths will be informative for explaining the departure of HATS-9b from the correlation. A more precise determination of the radius of HATS-9b is also required. The somewhat larger uncertainty in the radius is a result of the incomplete photometric follow-up for this system. The errors in the planet radius are governed at this point by the light-curve data, but future precise
measurements of the transit of HATS-9b will be able to lower this uncertainty until it becomes dominated by the uncertainties on the stellar parameters.

Future precise RV measurements of HATS-10b are required to determine a more precise mass of the planet and to explain the high jitter measured with FEROS and Coralie with respect to Subaru/HDS. One possible explanation may be the presence of another planetary companion. Subaru/HDS observations, which do not seem to show enhanced jitter, were performed in three continuous days, while Coralie and FEROS observations were separated by months and in this case the influence of a second more distant companion should be stronger. The jitter values quoted in Table 4.7 refer to RV uncertainties for each instrument that have to be added in quadrature to the formal RV errors in order for them to be consistent with the RV signal computed with the orbital parameters of the system.

4.4.1 K2 possibilities

Even though HATS-9b and HATS-10b are located in the nominal coordinates of Field 7 of K2, only HATS-9b falls on working silicon. A proposal to observe this star in short cadence was recently submitted. The high photometric precision of K2 will allow us to estimate a much more precise radius for HATS-9b, which will help us in determining if this planet is a true outlier in the correlation between planet radius, equilibrium temperature and planet mass. The high insolation of this planet makes it a very good target for measuring secondary transits and phase curve variations with K2, which will allow us to estimate the albedo and provide a more reliable estimate of its equilibrium temperature. Figure 4.9 shows a measure of the reflected light signature, \((R_p/a)^2\), for hot Jupiters observed by Kepler as a function of planetary radius. From this figure we can see that the potential of detecting reflected light signatures of HATS-9b is high and its amplitude should be similar to the one of the giant planets observed by Kepler.
so far. Other subtle photometric effects, like ellipsoidal variations, Doppler beaming and the measurement of asteroseismological frequencies, if present, will also be very valuable for the detailed characterization of this particular planet.

![Mass-radius diagram of giant TEPs](image1)

**Figure 4.6:** (Left): Mass-radius diagram of giant TEPs. HATS-9b is marked with a filled square and HATS-10b with a filled triangle. Iso-density curves are plotted with dashed lines for $\rho_P = \{0.25, 0.5, 1.0, 2.0, 4.0\}$ gr cm$^3$ and the 4.5 Gyr isochrones (Fortney et al. 2007) for core masses of 0 and 100 M$_\odot$ with solid lines. (Right): Equilibrium temperature versus radius diagram for giant TEPs. Again, HATS-9b is marked with a filled square and HATS-10b with a filled triangle.
Figure 4.7: Mass-radius diagram of giant TEPs having similar insolation levels to HATS-9b (1750 K < T_{eq} < 1900 K). HATS-9b is marked with a triangle. Filled symbols are coloured according to the metallicity of the host star. HATS-9b does not follow the correlation formed by the other hot Jupiters with similar irradiation levels.
Table 4.3: Relative radial velocities and bisector spans for HATS-9b

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\(^a\) S/N per resolution element near 5180 Å.

\(^b\) For Coralie and FEROS this is the systemic RV from fitting an orbit to the observations in Section 4.3.3. For ARCES and the du Pont Echelle it is the measured RV of the single observation. We do not provide this quantity for instruments for which only relative RVs are measured, or for WiFeS which was only used to measure stellar atmospheric parameters.

\(^c\) For high precision RV observations included in the orbit determination this is the RV residuals from the best-fit orbit, for other instruments used for reconnaissance spectroscopy this is an estimate of the precision.
Table 4.4: Relative radial velocities and bisector spans for HATS-10b

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<td>-75.00</td>
<td>29.00</td>
<td>315.0</td>
<td>21.0</td>
<td>0.170</td>
<td>Coralie</td>
</tr>
<tr>
<td>525.53878(^c)</td>
<td>57.00</td>
<td>39.00</td>
<td>462.0</td>
<td>24.0</td>
<td>0.422</td>
<td>Coralie</td>
</tr>
<tr>
<td>525.65573(^c)</td>
<td>-103.00</td>
<td>38.00</td>
<td>459.0</td>
<td>24.0</td>
<td>0.458</td>
<td>Coralie</td>
</tr>
</tbody>
</table>

\(^a\) S/N per resolution element near 5180 Å.

\(^b\) For Coralie and FEROS this is the systemic RV from fitting an orbit to the observations in Section 4.3.3. For ARCES and the du Pont Echelle it is the measured RV of the single observation. We do not provide this quantity for instruments for which only relative RVs are measured, or for WiFeS which was only used to measure stellar atmospheric parameters.

\(^c\) For High-precision RV observations included in the orbit determination this is the RV residuals from the best-fit orbit, for other instruments used for reconnaissance spectroscopy this is an estimate of the precision.
### Table 4.5: Light curve data for HATS-9 and HATS-10.

<table>
<thead>
<tr>
<th>Object</th>
<th>BJD$^{b}$</th>
<th>Mag$^c$</th>
<th>$\sigma_{\text{Mag}}$</th>
<th>Mag(orig)$^d$</th>
<th>Filter</th>
<th>Instrument</th>
</tr>
</thead>
<tbody>
<tr>
<td>HATS-9</td>
<td>55744.07098</td>
<td>$-0.00037$</td>
<td>0.00552</td>
<td>0.00000</td>
<td>$r$</td>
<td>HS</td>
</tr>
<tr>
<td>HATS-9</td>
<td>55749.81701</td>
<td>$-0.00018$</td>
<td>0.00572</td>
<td>0.00000</td>
<td>$r$</td>
<td>HS</td>
</tr>
<tr>
<td>HATS-9</td>
<td>55780.46237</td>
<td>0.00906</td>
<td>0.00604</td>
<td>0.00000</td>
<td>$r$</td>
<td>HS</td>
</tr>
<tr>
<td>HATS-9</td>
<td>55767.05534</td>
<td>$-0.01086$</td>
<td>0.00553</td>
<td>0.00000</td>
<td>$r$</td>
<td>HS</td>
</tr>
<tr>
<td>HATS-9</td>
<td>55696.18926</td>
<td>0.01787</td>
<td>0.00581</td>
<td>0.00000</td>
<td>$r$</td>
<td>HS</td>
</tr>
<tr>
<td>HATS-9</td>
<td>55657.88321</td>
<td>$-0.00168$</td>
<td>0.00549</td>
<td>0.00000</td>
<td>$r$</td>
<td>HS</td>
</tr>
<tr>
<td>HATS-9</td>
<td>55726.83440</td>
<td>0.00055</td>
<td>0.00619</td>
<td>0.00000</td>
<td>$r$</td>
<td>HS</td>
</tr>
<tr>
<td>HATS-9</td>
<td>55680.86732</td>
<td>0.01840</td>
<td>0.00534</td>
<td>0.00000</td>
<td>$r$</td>
<td>HS</td>
</tr>
<tr>
<td>HATS-9</td>
<td>55788.12454</td>
<td>0.00811</td>
<td>0.00716</td>
<td>0.00000</td>
<td>$r$</td>
<td>HS</td>
</tr>
<tr>
<td>HATS-9</td>
<td>55776.63287</td>
<td>$-0.00411$</td>
<td>0.00550</td>
<td>0.00000</td>
<td>$r$</td>
<td>HS</td>
</tr>
</tbody>
</table>

$^a$ Either HATS-9, or HATS-10.

$^b$ Barycentric Julian Date is computed directly from the UTC time without correction for leap seconds.

$^c$ The out-of-transit level has been subtracted. For observations made with the HATSouth instruments (identified by “HS” in the “Instrument” column) these magnitudes have been corrected for trends using the EPD and TFA procedures applied prior to fitting the transit model. This procedure may lead to an artificial dilution in the transit depths. For HATS-9 our fit is consistent with no dilution, for HATS-10 the HATSouth transit depth is $\sim 93\%$ that of the true depth. For observations made with follow-up instruments (anything other than “HS” in the “Instrument” column), the magnitudes have been corrected for a quadratic trend in time fit simultaneously with the transit.

$^d$ Raw magnitude values without correction for the quadratic trend in time. These are only reported for the follow-up observations.
Table 4.6: Stellar parameters for HATS-9 and HATS-10.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>HATS-9</th>
<th>HATS-10</th>
<th>Source</th>
</tr>
</thead>
<tbody>
<tr>
<td>General properties</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>2MASS-ID</td>
<td>2MASS 19231442-2009587</td>
<td>2MASS 19371363-2212161</td>
<td></td>
</tr>
<tr>
<td>GSC-ID</td>
<td>GSC 6305-02502</td>
<td>GSC 6311-00085</td>
<td></td>
</tr>
<tr>
<td>R.A. (J2000)</td>
<td>19h 23m 14.28s</td>
<td>19h 37m 13.80s</td>
<td>2MASS</td>
</tr>
<tr>
<td>Dec. (J2000)</td>
<td>-20°09'58.7&quot;</td>
<td>-22°12'16.1&quot;</td>
<td>2MASS</td>
</tr>
<tr>
<td>(\mu_{\alpha}) (mas yr(^{-1}))</td>
<td>0.3±4.3</td>
<td>3.1±1.3</td>
<td>UCAC4</td>
</tr>
<tr>
<td>(\mu_{\delta}) (mas yr(^{-1}))</td>
<td>-1.9±2.8</td>
<td>-3.2±1.6</td>
<td>UCAC4</td>
</tr>
<tr>
<td>Spectroscopic properties</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>(T_{\text{eff}}) (K)</td>
<td>5366±70</td>
<td>5880±120</td>
<td>ZASPE(^a)</td>
</tr>
<tr>
<td>[Fe/H]</td>
<td>0.34±0.05</td>
<td>0.15±0.10</td>
<td>ZASPE</td>
</tr>
<tr>
<td>(v\sin i) (km s(^{-1}))</td>
<td>4.58±0.90</td>
<td>5.68±0.70</td>
<td>ZASPE</td>
</tr>
<tr>
<td>(v_{\text{mic}}) (km s(^{-1}))</td>
<td>4.6</td>
<td>3.8</td>
<td>Assumed(^b)</td>
</tr>
<tr>
<td>(v_{\text{mac}}) (km s(^{-1}))</td>
<td>1.0</td>
<td>1.0</td>
<td>Assumed(^c)</td>
</tr>
<tr>
<td>(\gamma_{\text{RV}}) (km s(^{-1}))</td>
<td>-10.644 ± 0.013</td>
<td>-28.088 ± 0.024</td>
<td>Coralie,FES</td>
</tr>
<tr>
<td>Photometric properties</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>(B) (mag)</td>
<td>14.080 ± 0.010</td>
<td>13.820 ± 0.010</td>
<td>APASS(^d)</td>
</tr>
<tr>
<td>(V) (mag)</td>
<td>13.276 ± 0.010</td>
<td>13.113 ± 0.010</td>
<td>APASS(^d)</td>
</tr>
<tr>
<td>(g) (mag)</td>
<td>13.629 ± 0.010</td>
<td>13.448 ± 0.010</td>
<td>APASS(^d)</td>
</tr>
<tr>
<td>(r) (mag)</td>
<td>13.072 ± 0.030</td>
<td>12.967 ± 0.010</td>
<td>APASS(^d)</td>
</tr>
<tr>
<td>(i) (mag)</td>
<td>12.865 ± 0.010</td>
<td>12.781 ± 0.010</td>
<td>APASS(^d)</td>
</tr>
<tr>
<td>(J) (mag)</td>
<td>11.885 ± 0.022</td>
<td>11.866 ± 0.024</td>
<td>2MASS</td>
</tr>
<tr>
<td>(H) (mag)</td>
<td>11.558 ± 0.027</td>
<td>11.568 ± 0.024</td>
<td>2MASS</td>
</tr>
<tr>
<td>(K_s) (mag)</td>
<td>11.479 ± 0.022</td>
<td>11.511 ± 0.025</td>
<td>2MASS</td>
</tr>
<tr>
<td>Derived properties</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>(M_\star) (M_\odot)</td>
<td>1.030 ± 0.039</td>
<td>1.101 ± 0.054</td>
<td>YY+(\rho_\star)+ZASPE(^e)</td>
</tr>
<tr>
<td>(R_\star) (R_\odot)</td>
<td>1.503(^{+0.101}_{-0.043})</td>
<td>1.105(^{+0.055}_{-0.040})</td>
<td>YY+(\rho_\star)+ZASPE (^f)</td>
</tr>
<tr>
<td>(\log g_\star) (cgs)</td>
<td>4.095 ± 0.038</td>
<td>4.392 ± 0.032</td>
<td>YY+(\rho_\star)+ZASPE(^f)</td>
</tr>
<tr>
<td>(\rho_\star) (g cm(^{-3}))</td>
<td>0.427(^{+0.030}_{-0.070})</td>
<td>1.15(^{+0.12}_{-0.16})</td>
<td>YY+(\rho_\star)+ZASPE(^f)</td>
</tr>
<tr>
<td>(L_\star) (L_\odot)</td>
<td>1.70(^{+0.24}_{-0.16})</td>
<td>1.31 ± 0.18</td>
<td>YY+(\rho_\star)+ZASPE(^f)</td>
</tr>
<tr>
<td>(M_\gamma) (mag)</td>
<td>4.33 ± 0.15</td>
<td>4.52 ± 0.16</td>
<td>YY+(\rho_\star)+ZASPE(^f)</td>
</tr>
<tr>
<td>(M_K) (mag,ESO)</td>
<td>2.49 ± 0.13</td>
<td>3.05 ± 0.10</td>
<td>YY+(\rho_\star)+ZASPE(^f)</td>
</tr>
<tr>
<td>Age (Gyr)</td>
<td>10.8 ± 1.5</td>
<td>3.3 ± 1.7</td>
<td>YY+(\rho_\star)+ZASPE(^f)</td>
</tr>
<tr>
<td>(A_V) (mag)</td>
<td>0.000 ± 0.011</td>
<td>0.112 ± 0.075</td>
<td>YY+(\rho_\star)+ZASPE(^f)</td>
</tr>
<tr>
<td>Distance (pc)</td>
<td>622(^{+42}_{-30})</td>
<td>496 ± 24</td>
<td>YY+(\rho_\star)+ZASPE(^f)</td>
</tr>
</tbody>
</table>

\(^a\) These parameters rely primarily on ZASPE, but have a small dependence also on the iterative analysis incorporating the isochrone search and global modeling of the data.

\(^b\) Computed following Valenti & Fischer (2005).

\(^c\) Husser et al. (2013).

\(^d\) From APASS DR6 for HATS-9, HATS-10 as listed in the UCAC 4 catalog (Zacharias et al. 2012).

\(^e\) Based on the YY isochrones (Yi et al. 2001), \(\rho_\star\) as a luminosity indicator, and the ZASPE results.

\(^f\) Primarily determined from the global fit to the light curves and RV data. The value shown here also has a slight dependence on the stellar models and ZASPE parameters due to restricting the posterior distribution to combinations of \(\rho_\star\)+\(T_{\text{eff}}\)+[Fe/H]that match to a YY stellar model.
Table 4.7: Orbital and planetary parameters for HATS-9b and HATS-10b.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>HATS-9</th>
<th>HATS-10</th>
</tr>
</thead>
<tbody>
<tr>
<td>Light curve</td>
<td></td>
<td></td>
</tr>
<tr>
<td>P (days)</td>
<td>1.9153073 ± 0.0000052</td>
<td>3.3128460 ± 0.0000058</td>
</tr>
<tr>
<td>T_e (BJD)</td>
<td>2456124.25896 ± 0.00086</td>
<td>2456457.88193 ± 0.00022</td>
</tr>
<tr>
<td>T_{14} (days)</td>
<td>0.1457 ± 0.0024</td>
<td>0.1253 ± 0.0011</td>
</tr>
<tr>
<td>T_{12} = T_{34} (days)</td>
<td>0.0106 ± 0.0015</td>
<td>0.01157 ± 0.00100</td>
</tr>
<tr>
<td>a/R_<em>, (b^2), b \equiv a \cos i/R_</em></td>
<td>4.36^{+0.10}_{-0.25}</td>
<td>8.73^{+0.29}_{-0.44}</td>
</tr>
<tr>
<td>R_p/R_*</td>
<td>0.0725 ± 0.0041</td>
<td>0.0903 ± 0.0013</td>
</tr>
<tr>
<td>(b^2), b \equiv a \cos i/R_*</td>
<td>0.071^{+0.112}_{-0.050}</td>
<td>0.113^{+0.087}_{-0.059}</td>
</tr>
<tr>
<td>(b^2) \equiv R_\star</td>
<td>0.27^{+0.16}_{-0.12}</td>
<td>0.34^{+0.11}_{-0.10}</td>
</tr>
<tr>
<td>i (deg)</td>
<td>86.5^{+1.6}_{-2.5}</td>
<td>87.79 ± 0.72</td>
</tr>
<tr>
<td>Limb-darkening^a</td>
<td></td>
<td></td>
</tr>
<tr>
<td>c_{1, g} \ (linear term)</td>
<td>...</td>
<td>0.5380</td>
</tr>
<tr>
<td>c_{2, g} \ (quadratic term)</td>
<td>...</td>
<td>0.2487</td>
</tr>
<tr>
<td>c_{1, r}</td>
<td>0.4688</td>
<td>0.3459</td>
</tr>
<tr>
<td>c_{2, r}</td>
<td>0.2596</td>
<td>0.3349</td>
</tr>
<tr>
<td>c_{1, i}</td>
<td>0.3533</td>
<td>0.2587</td>
</tr>
<tr>
<td>c_{2, i}</td>
<td>0.2892</td>
<td>0.3388</td>
</tr>
<tr>
<td>c_{1, z}</td>
<td>...</td>
<td>0.1978</td>
</tr>
<tr>
<td>c_{2, z}</td>
<td>...</td>
<td>0.3360</td>
</tr>
<tr>
<td>c_{1, R}</td>
<td>0.4369</td>
<td>0.3216</td>
</tr>
<tr>
<td>c_{2, R}</td>
<td>0.2687</td>
<td>0.3371</td>
</tr>
<tr>
<td>RV parameters</td>
<td></td>
<td></td>
</tr>
<tr>
<td>K \ (m\ s^{-1})</td>
<td>133.5 ± 3.4</td>
<td>67 ± 10</td>
</tr>
<tr>
<td>e</td>
<td>&lt; 0.129</td>
<td>&lt; 0.501</td>
</tr>
<tr>
<td>RV jitter HDS \ (m\ s^{-1})</td>
<td>0.1 ± 5.2</td>
<td>0.00 ± 0.53</td>
</tr>
<tr>
<td>RV jitter FEROS \ (m\ s^{-1})</td>
<td>0.0 ± 1.7</td>
<td>38 ± 28</td>
</tr>
<tr>
<td>RV jitter Coralie \ (m\ s^{-1})</td>
<td>0.0 ± 1.1</td>
<td>45 ± 23</td>
</tr>
<tr>
<td>Planetary parameters</td>
<td></td>
<td></td>
</tr>
<tr>
<td>M_p \ (M_J)</td>
<td>0.837 ± 0.029</td>
<td>0.526 ± 0.081</td>
</tr>
<tr>
<td>R_p \ (R_J)</td>
<td>1.065 ± 0.098</td>
<td>0.969^{+0.061}_{-0.045}</td>
</tr>
<tr>
<td>C(M_p, R_p)^b</td>
<td>0.48</td>
<td>0.02</td>
</tr>
<tr>
<td>(\rho_p) \ (g \cm^{-3})</td>
<td>0.85 ± 0.19</td>
<td>0.70 ± 0.15</td>
</tr>
<tr>
<td>log (g_p) \ (cgs)</td>
<td>3.253 ± 0.068</td>
<td>3.140 ± 0.082</td>
</tr>
<tr>
<td>a \ (AU)</td>
<td>0.03048 ± 0.00038</td>
<td>0.04491 ± 0.00074</td>
</tr>
<tr>
<td>T_{eq} \ (K)</td>
<td>1823^{+52}_{-35}</td>
<td>407 ± 39</td>
</tr>
<tr>
<td>log_{10}(F) \ (cgs)^c</td>
<td>9.397^{+0.049}_{-0.033}</td>
<td>8.947 ± 0.047</td>
</tr>
</tbody>
</table>

^a Values for a quadratic law, adopted from the tabulations by Claret (2004) according to the spectroscopic (ZASPE) parameters listed in Table 4.6.

^b Correlation coefficient between the planetary mass \(M_p\) and radius \(R_p\), estimated from the posterior parameter distribution.

^c Incoming flux per unit surface area, averaged over the orbit.
Figure 4.8: Radius as function of the age of the system for hot Jupiters having $0.5 M_J < M_p < 2 M_J$, $P<10$ days and an age estimation with a precision better than 40%. Green lines are the theoretical models of Fortney et al. (2007) for $M_p=1 M_J$, $a = 0.02$AU and a core mass of 0 (dashed) and 50 (solid) times the mass of the earth. The red line is an empirical relation computed with these data points. HATS-9b is marked with a triangle. Hot Jupiters older than 3 Gyr follow the contraction of their radius over time but the observed contraction rate is steeper than the one predicted from the theoretical models. The theoretical radii for Hot Jupiters with ages greater than 10 Gyr (like HATS-9b) is consistent with the observations.
Figure 4.9: Reflected light signature as function of the planetary radius for the hot Jupiters observed with Kepler. The symbols are colored according to the planetary mass. HATS-9b is marked with a triangle. Given that the photometric precision of K2 is similar to the one of the original Kepler mission, phase curve variations and secondary the secondary transit of HATS-9b should be measured by K2.
Chapter 5

HATS-17b: A Transiting Compact Warm Jupiter in a 16.3 days Circular Orbit

Abstract

We report the discovery of HATS-17b, the first transiting warm Jupiter of the HATSouth network. HATS-17b transits its bright (V=12.4) G-type ($M_*=1.131\pm0.03\ M_\odot$, $R_*=1.091^{+0.070}_{-0.046}\ R_\odot$) metal-rich ([Fe/H]=+0.3 dex) host star in a circular orbit with a period of $P=16.2546$ days. HATS-17b has a very compact radius of $0.777\pm0.056\ R_J$ given its Jupiter-like mass of $1.338\pm0.065\ M_J$. Up to 50% of the mass of HATS-17b may be composed of heavy elements in order to explain its high density with current models of planetary structure. HATS-17b is the longest period transiting planet discovered to date by a ground-based photometric survey, and is one of the brightest transiting warm Jupiter systems known. The brightness of HATS-17 will al-

\footnote{Based on Brahm, R., Jordán, A., Bakos, G., 2015, submitted to AJ}
low detailed follow-up observations to characterize the orbital geometry of the system and the atmosphere of the planet.

5.1 Introduction

The detection of numerous extrasolar giant planets has brought forth several theoretical challenges regarding their formation, structure and evolution. One of these challenges arises from the fact that for over 20 years, radial velocity (RV) surveys have been discovering large number of giant planets found to orbit their host stars at short distances (< 1 AU), where they are highly unlikely to be formed. Hot Jupiters having semi-major axes of ~0.03 AU, are the most extreme cases. Short period giant planets are thought to be formed at several AU, beyond the so-called snow line, where sufficient solid material is available to build ~10 $M_\oplus$ cores that accrete their gaseous envelopes from the protoplanetary disc before it is dispersed (e.g., Rafikov 2006). The subsequent inward migration can be produced by the exchange of angular momentum with the same protoplanetary disc (Goldreich & Tremaine 1980) and/or by gravitational interactions with other stellar or planetary bodies which produce high eccentricity migration mechanisms, in which eccentricities are excited and the semi-major axis decreases due to tidal interactions with the star (Rasio & Ford 1996; Wu & Lithwick 2011; Fabrycky & Tremaine 2007; Petrovich 2015). These two migration mechanisms predict different end products. While disc migration should produce circular orbits in which the angular momentum vector of the orbit is aligned with the spin of the star, high eccentricity migration mechanisms can produce planets with a broad distribution of eccentricities and misalignment angles.

Transiting extrasolar planets (TEPs) are fundamental objects for constraining migration scenarios, because the measurement of the Rossiter-McLaughlin effect (Rossiter 1924; McLaughlin 1924) allows the determination of the sky-projected angle between the orbital and stellar spins.
This angle has been determined for several transiting hot Jupiters showing that while most of the systems have well aligned prograde orbits, an important fraction of them is found to present measurable misalignments (Hébrard et al. 2008; Queloz et al. 2010; Winn et al. 2010). Hot Jupiters, however, are not optimal systems for discriminating between migration mechanisms. The tidal or magnetic interactions with the host star which can arise due to their extremely close-in orbits can be responsible for not only circularising the orbit but also potentially re-aligning the spin of the star with the orbit of the planet and thereby affecting the final state of the system (Dawson 2014). Transiting giant planets with larger semi-major axes ($a > 0.1$ AU), on the other hand, do not suffer from strong interactions with their stars and can be used for measuring a more pristine final state of the migration process.

While TEPs can be used to refine the geometrical configuration of the orbits, arguably their most important feature is that their radii can be derived from the transit depth if the radii of the stellar hosts are known. The estimation of the radius, coupled with the measurement of the planetary mass from RV observations, allows the computation of the bulk density of the planet and the possibility of inferring properties about its internal structure and composition. Another theoretical challenge arose with the discovery of the first transiting extrasolar planets. While theories of giant planet evolution predicted $\approx 1 \, R_J$ for planets with masses $\approx 1 \, M_J$, ages above 1 Gyr and no cores (Burrows et al. 2007), observations of close-in transiting giant planets revealed a broad distribution of planetary radii, with some of them reaching even twice the radius of Jupiter, like HAT-P-32b (Hartman et al. 2011). Others had radii more compact than expected from theoretical models without solid cores, like WASP-59b with $R_p=0.78 \, R_J$ (Hébrard et al. 2013).

The origin of these anomalies in the measured radii of giant exoplanets have been extensively investigated, but there are no conclusive theories that are able to explain simultaneously the
variety of systems. A central solid core is commonly invoked to explain the radii of compact giant planets, while the proximity of the planets to their stellar hosts is probably responsible of generating the inflated planets via a variety of mechanisms including extra power deposited at some depth via, e.g., tidal or radiative heating mechanisms, enhanced atmospheric opacities, suppression of convective heat loss, among others (for a review see Spiegel & Burrows 2013). The principal problem of favouring one inflating mechanism over another comes from the degeneracies in the modelled radius that arise from the unknown mass of the central core. Kovács et al. (2010) found that the inflation of the radius stops being efficient for incident stellar fluxes weaker than $\langle F \rangle \approx 2 \times 10^8$ erg s$^{-1}$ cm$^{-2}$ (see also Demory & Seager 2011). Detections of giant planets with irradiation values below this limit are very valuable because the interior structure of the planet can be estimated without assumptions about extra energy sources. Furthermore, the distribution of core masses determined for weakly irradiated giant planets can then be extrapolated to highly irradiated planets to constrain inflation mechanisms.

As stated above, giant TEPs with moderately long orbital periods (warm Jupiters) are unique test objects for validating structure and migrations theories. However, from the total of $\approx 1900$ confirmed or validated planets discovered to date, only 23 transiting planets have $P > 10$ days, $R_p > 0.5$ $R_J$ and measured masses greater than 0.25 $M_J$. Moreover, most of these interesting systems were discovered with the space based missions *Kepler* and CoRoT around faint host stars ($V > 14$) hindering the measurement of precise RV variations, and limiting future detailed follow-up observations.

On the other hand, the detection of transiting warm Jupiters from the ground is a challenging task. Only two such planets with $P > 10$ days are known, originally discovered by RV programs and then later found to transit. These are: HD17156 with $P = 22.6$ days (Fischer et al. 2007) and HD80606 with $P = 115$ days (Naef et al. 2001). The small number of detections is due to
the fact that the transit probability decreases inversely with the semi-major axis. Ground based transit surveys can deal in principle with this low probability problem by monitoring many more stars than the RV programs do, but the diurnal cycle strongly limits the recovery of \( P > 10 \) days planets for common one-site based surveys. The use of longitudinal networks of telescopes is a way of counteracting the limitations imposed by the diurnal cycle. Indeed, the transiting extrasolar planet with the longest period discovered previous to the present study by a ground based transit survey was HAT-P-15b (Kovács et al. 2010) with \( P = 10.8 \) days. This system was detected by the two-site-based HATNet survey (Bakos et al. 2004).

One of the main goals of the HATSouth survey (Bakos et al. 2013) is to expand the parameter space of well characterized transiting planets around moderately bright stars. The first results in this regard have started to appear. HATS-6b (Hartman et al. 2015b) is one of only four transiting giant planets discovered around stars with masses \( M_\star < 0.6 M_\odot \), while HATS-7b (Bakos et al. 2015) and HATS-8b (Bayliss et al. 2015) are now two among the handful of well characterized transiting super Neptunes. Having three locations with large longitude separation in the southern hemisphere, the HATSouth survey is able to monitor, almost continuously, selected fields on the sky for \( \sim 4 \) months per year, substantially increasing the probability of detecting transiting extrasolar planets with periods longer than 10 days (Bakos et al. 2013). In this paper we present the discovery of HATS-17b, the first transiting warm Jupiter of the HATSouth survey. With an orbital period of \( P \sim 16.3 \) days, it is the longest period transiting extrasolar planet discovered by a ground-based photometric survey.

The paper is structured as follows. In Section 5.2 we describe the photometric and spectroscopic observations that allowed the discovery and confirmation of HATS-17b. In Section 5.3 we explain the tools that were used to estimate the physical parameters of HATS-17b and its host star. Finally, in Section 5.4 we place the physical properties of HATS-17b in the context of the
transiting exoplanets previously detected and outline possible follow-up observations for further characterizing this system.

### 5.2 Observations

#### 5.2.1 Photometry

**Photometric detection**

The star HATS-17 (Table 5.4) was observed by HATSouth instruments between UT 2011 April 26 and UT 2012 July 31 using the HS-2, HS-4, and HS-6 units at LCO in Chile, the H.E.S.S. site in Namibia, and SSO in Australia, respectively. The number of observations obtained with each instrument, effective cadence, and photometric precision are listed in Table 5.1. The data were reduced to trend-filtered light curves using the aperture photometry procedure described by Penev et al. (2013) and making use of External Parameter Decorrelation (EPD; Bakos et al. 2010) and the Trend Filtering Algorithm (TFA; Kovács et al. 2005) to remove systematic variations. We searched for transits using the Box-fitting Least Squares (BLS; Kovács et al. 2002) algorithm, and detected a $P = 16.2546$ day periodic transit signal in the light curve of HATS-17 (Figure 5.1; the data are available in Table 5.2).

**Photometric follow-up**

Given the quality of the HATSouth detection, follow-up observations of the transit were required in order to confirm that the signal is compatible with a transiting planet, and to precisely determine the physical parameters of the system.

Due to the long period of the discovered transit signal and the long duration of the transits (5.2
Table 5.1: Summary of photometric observations of HATS-17

<table>
<thead>
<tr>
<th>Instrument/Field</th>
<th>Date Range</th>
<th># Images</th>
<th>Cadence (sec)</th>
<th>Filter</th>
<th>Precision (mmag)</th>
</tr>
</thead>
<tbody>
<tr>
<td>HS-2/G700 (LCO)</td>
<td>2011 Apr–2012 Jul</td>
<td>4579</td>
<td>292</td>
<td>r</td>
<td>5.8</td>
</tr>
<tr>
<td>HS-4/G700 (HESS)</td>
<td>2011 Jul–2012 Jul</td>
<td>3759</td>
<td>301</td>
<td>r</td>
<td>6.4</td>
</tr>
<tr>
<td>HS-6/G700 (SSO)</td>
<td>2011 May–2012 Jul</td>
<td>1499</td>
<td>300</td>
<td>r</td>
<td>6.5</td>
</tr>
<tr>
<td>PEST 0.3 m (Perth, AU)</td>
<td>2015 Apr 26</td>
<td>215</td>
<td>132</td>
<td>$R_C$</td>
<td>2.4</td>
</tr>
<tr>
<td>LCOGT 1 m/sinistro (CTIO)</td>
<td>2015 May 13</td>
<td>54</td>
<td>105</td>
<td>i</td>
<td>1.3</td>
</tr>
<tr>
<td>Swope 1 m/e2v (LCO)</td>
<td>2015 May 29</td>
<td>141</td>
<td>129</td>
<td>i</td>
<td>3.8</td>
</tr>
<tr>
<td>Swope 1 m/e2v (LCO)</td>
<td>2015 Jul 17</td>
<td>79</td>
<td>99</td>
<td>i</td>
<td>1.6</td>
</tr>
<tr>
<td>LCOGT 1 m/sinistro (CTIO)</td>
<td>2015 Jul 17</td>
<td>71</td>
<td>162</td>
<td>i</td>
<td>0.8</td>
</tr>
</tbody>
</table>

* For the HATSouth observations we list the HS instrument used to perform the observations and the pointing on the sky. HS-2 is located at Las Campanas Observatory in Chile, HS-4 at the H.E.S.S. gamma-ray telescope site in Namibia, and HS-6 at Siding Spring Observatory in Australia. Field G700 is one of 838 discrete pointings used to tile the sky for the HATNet and HATSouth projects. This particular field is centered at R.A. 13.2 hr and Dec. –45.0°.

* The r.m.s. scatter of the residuals from our best fit transit model for each light curve at the cadence indicated in the table.

The photometric follow-up for this kind of TEP candidate brings more difficulties than the ones presented in more typical ($P < 5$ days) candidates. For this reason a high priority photometric follow-up campaign for HATS-17 started only after the spectroscopic observations described in Section 5.2.2 showed an orbital variation in RV in phase with the photometric ephemeris.

The first photometric follow-up light curve of this system was obtained with the 0.3 m Perth Exoplanet Survey Telescope (PEST)\(^2\) located near Perth. The unbinned precision of 2.5 mmag allowed the measurement of a full $\approx 5$ mmag flat-bottom transit.

Another two partial transits were then acquired with the LCOGT 1 m telescope network, specifically with the telescope at Cerro Tololo Inter-American Observatory (CTIO), and with the

\(^2\)http://www.cantab.net/users/tgtan/
Figure 5.1: Unbinned instrumental $r$ band light curve of HATS-17 folded with the period $P = 16.2546107$ days resulting from the global fit described in Section 5.3. The solid line shows the best-fit transit model (see Section 5.3). In the lower panel we zoom-in on the transit; the dark filled points here show the light curve binned in phase using a bin-size of 0.002. The signal is consistent with flat-bottom transit with a depth of 5 mmag.

Swope 1 m coupled with the e2v camera at Las Campanas Observatory (LCO). The former registered only the egress of the transit which was helpful in refining the ephemeris of the system, while the latter obtained one ingress and part of the transit but the weather conditions were suboptimal and did not allow for a substantial improvement of the measured transit parameters.

Finally, two partial transits of the same event were measured with high photometric precision
Chapter 5. HATS-17b

(≈ 1 mmag) in one of the last chances to observe it during the season. The observations were
performed with the same two telescopes that registered the previous partial transits and they
obtained a fraction of the bottom part of the transit and the egress. These observations revealed a
clear transit with a depth of ≈ 6 mmag and improved substantially the precision of the measured
transit parameters.

All the photometric observations are summarized in Table 5.1. Table 5.2 provides the light curve
data, while the light curves are compared to our best-fit model in Figure 5.2. All the facilities
used for high precision photometric follow-up have been previously used by HATSouth; the in-
strument specifications, observation strategies and adopted reduction procedures can be found in
Zhou et al. (2014b), Bakos et al. (2015) and Bayliss et al. (2015) for PEST, LCOGT 1 m/sinistro
(CTIO), and Swope 1 m/e2v, respectively. Given that there were no evident close companions
to HATS-17, all photometric follow-up observations were acquired with defocusing.

5.2.2 Spectroscopy

An extensive follow-up campaign is required for validating the planetary nature of HATSouth
transiting candidates. Transit-like signals in the light curves can be produced by artifacts in the
data or different configurations of stellar eclipsing binaries and background stars. Spectroscopic
observations are used for characterizing the properties of the star and to determine the mass and
orbital parameters of the planets from RV curves.

The first spectroscopic observation of HATS-17 was carried out by the WiFeS instrument on the
ANU 2.3 m telescope at SSO (Dopita et al. 2007). A single low resolution (R=3000) spectrum
was enough for a first estimation of the stellar parameters of HATS-17. Following the reduc-
tions and analysis procedures detailed in Bayliss et al. (2013), the computed stellar atmospheric
Figure 5.2: Left: Unbinned follow-up transit light curves of HATS-17. The dates, filters and instruments used for each event are indicated. Curves after the first are shifted for clarity. Our best fit is shown by the solid lines. Right: Residuals from the fits in the same order as the curves at left.

parameters were $T_{\text{eff}} = 5315 \pm 300 \, \text{K}$, $\log g = 4.4 \pm 0.3 \, \text{dex}$ and $\text{[Fe/H]} = -0.5 \pm 0.5 \, \text{dex}$. After HATS-17b was identified as a single-lined G-type dwarf, five additional $R=7000$ spectra were obtained with the same instrument in order to measure RV variations. These five RV points were consistent with no variation at the $\sim 2 \, \text{km s}^{-1}$ level, which shows that the observed photometric signal is not produced by an unblended eclipsing stellar mass companion.
Table 5.2: Differential photometry of HATS-17

<table>
<thead>
<tr>
<th>BJD (2400000+)</th>
<th>Mag(^a)</th>
<th>(\sigma_{\text{Mag}})</th>
<th>Mag(_{\text{orig}})(^b)</th>
<th>Filter</th>
<th>Instrument</th>
</tr>
</thead>
<tbody>
<tr>
<td>56123.25166</td>
<td>-0.00660</td>
<td>0.00285</td>
<td>(\cdots)</td>
<td>(r)</td>
<td>HS</td>
</tr>
<tr>
<td>56074.48974</td>
<td>0.00167</td>
<td>0.00334</td>
<td>(\cdots)</td>
<td>(r)</td>
<td>HS</td>
</tr>
<tr>
<td>56123.25650</td>
<td>0.00042</td>
<td>0.00287</td>
<td>(\cdots)</td>
<td>(r)</td>
<td>HS</td>
</tr>
<tr>
<td>56074.49324</td>
<td>0.00716</td>
<td>0.00339</td>
<td>(\cdots)</td>
<td>(r)</td>
<td>HS</td>
</tr>
<tr>
<td>56123.26027</td>
<td>-0.00035</td>
<td>0.00284</td>
<td>(\cdots)</td>
<td>(r)</td>
<td>HS</td>
</tr>
<tr>
<td>56074.49672</td>
<td>-0.00865</td>
<td>0.00337</td>
<td>(\cdots)</td>
<td>(r)</td>
<td>HS</td>
</tr>
<tr>
<td>56123.26373</td>
<td>-0.00323</td>
<td>0.00289</td>
<td>(\cdots)</td>
<td>(r)</td>
<td>HS</td>
</tr>
<tr>
<td>56074.50208</td>
<td>-0.00251</td>
<td>0.00346</td>
<td>(\cdots)</td>
<td>(r)</td>
<td>HS</td>
</tr>
<tr>
<td>56123.26876</td>
<td>-0.00040</td>
<td>0.00286</td>
<td>(\cdots)</td>
<td>(r)</td>
<td>HS</td>
</tr>
<tr>
<td>56074.50592</td>
<td>0.00139</td>
<td>0.00342</td>
<td>(\cdots)</td>
<td>(r)</td>
<td>HS</td>
</tr>
</tbody>
</table>

\(^a\) The out-of-transit level has been subtracted. For the HATSouth light curve (rows with "HS" in the Instrument column), these magnitudes have been detrended using the EPD and TFA procedures prior to fitting a transit model to the light curve. Primarily as a result of this detrending, but also due to blending from neighbors, the apparent HATSouth transit depth is somewhat shallower than that of the true depth in the Sloan \(r\) filter (the apparent depth is 79% that of the true depth). For the follow-up light curves (rows with an Instrument other than "HS") these magnitudes have been detrended with the EPD procedure, carried out simultaneously with the transit fit (the transit shape is preserved in this process).

\(^b\) Raw magnitude values without application of the EPD procedure. This is only reported for the follow-up light curves.

This table is available in the HATSouth website at http://www.hatsouth.org.

Once HATS-17 passed the reconnaissance spectroscopy filter of our follow-up structure, further spectroscopic characterisation of the HATS-17 system was performed with facilities capable of measuring RV variations produced by the gravitational tug of a giant planet mass companion. Several high resolution spectra were acquired with three spectrographs installed in the ESO La Silla observatory. We obtained 11 spectra using HARPS at the ESO 3.6 m telescope, 8 spectra using CORALIE (Queloz et al. 2001) at the Euler 1.2 m telescope and 2 spectra with
FEROS (Kaufer & Pasquini 1998) at the MPG 2.2 m telescope. The data for these 3 instruments were reduced and analysed with the CERES pipelines (see Chapter 2), which process in an homogeneous and robust manner data obtained from different echelle spectrographs. Besides the reduced spectra, this pipeline delivers precise RV measurements, bisector span (BS) values from the cross-correlation peak and an estimation of the stellar atmospheric parameters. RV and BS values are presented in Table 5.3 with their corresponding uncertainties. As shown in the top panel of Figure 5.3, the RV measurements phase cleanly with the photometric ephemeris with an amplitude compatible with the one produced by a Jovian planet in an almost circular orbit. The middle panel of Figure 5.3 shows the residuals of the measured RV values and the best fit model, while the bottom panel confirms that the BS values are not responsible for the measured RV variations. The correlation coefficient between RV and BS values is $-0.2$ with a 95% confidence interval extending from $-0.596$ to $0.505$ obtained from a bootstrap simulation. The mean atmospheric parameters obtained from the 3 spectrographs were: $T_{\text{eff}} = 5705 \pm 118$ K, $\log g = 4.14 \pm 0.25$ dex and $[Fe/H] = 0.27 \pm 0.11$ dex, where the errors in the parameters are computed from the dispersion of the 21 observations. These atmospheric parameters computed from high resolution spectra show that HATS-17 is significantly hotter and more metal rich than we had previously estimated based on our initial WIFES spectrum.

5.3 Analysis

We analyzed the photometric and spectroscopic observations of HATS-17 to determine the parameters of the system using the standard procedures developed for HATNet and HATSouth (see Bakos et al. 2010, with modifications described by Hartman et al. 2012).

High-precision stellar atmospheric parameters were measured from the FEROS spectra using
Table 5.3: Relative radial velocities and bisector span measurements of HATS-17

<table>
<thead>
<tr>
<th>BJD</th>
<th>RV$^a$ (m s$^{-1}$)</th>
<th>$\sigma_{RV}$ (m s$^{-1}$)</th>
<th>BS$^b$ (m s$^{-1}$)</th>
<th>$\sigma_{BS}$ (m s$^{-1}$)</th>
<th>Phase</th>
<th>Instrument</th>
</tr>
</thead>
<tbody>
<tr>
<td>1067.79423</td>
<td>75.97</td>
<td>8.00</td>
<td>-30.0</td>
<td>32.0</td>
<td>0.609</td>
<td>HARP5</td>
</tr>
<tr>
<td>1068.83188</td>
<td>84.97</td>
<td>5.00</td>
<td>0.0</td>
<td>22.0</td>
<td>0.673</td>
<td>HARP5</td>
</tr>
<tr>
<td>1068.89436</td>
<td>100.97</td>
<td>5.00</td>
<td>3.0</td>
<td>20.0</td>
<td>0.677</td>
<td>HARP5</td>
</tr>
<tr>
<td>1069.85983</td>
<td>99.97</td>
<td>8.00</td>
<td>-3.0</td>
<td>30.0</td>
<td>0.736</td>
<td>HARP5</td>
</tr>
<tr>
<td>1069.89514</td>
<td>85.97</td>
<td>7.00</td>
<td>-29.0</td>
<td>30.0</td>
<td>0.738</td>
<td>HARP5</td>
</tr>
<tr>
<td>1070.82342</td>
<td>91.97</td>
<td>4.00</td>
<td>4.0</td>
<td>16.0</td>
<td>0.795</td>
<td>HARP5</td>
</tr>
<tr>
<td>1071.84990</td>
<td>74.97</td>
<td>4.00</td>
<td>-11.0</td>
<td>16.0</td>
<td>0.859</td>
<td>HARP5</td>
</tr>
<tr>
<td>1072.85895</td>
<td>43.97</td>
<td>4.00</td>
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<td>14.0</td>
<td>0.921</td>
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</tr>
<tr>
<td>1075.83710</td>
<td>-110.14</td>
<td>17.00</td>
<td>38.0</td>
<td>27.0</td>
<td>0.104</td>
<td>Coralie</td>
</tr>
<tr>
<td>1076.82996</td>
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<td>16.00</td>
<td>-20.0</td>
<td>25.0</td>
<td>0.165</td>
<td>Coralie</td>
</tr>
<tr>
<td>1077.81340</td>
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<td>5.0</td>
<td>29.0</td>
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</tr>
<tr>
<td>1078.82533</td>
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<td>25.0</td>
<td>0.288</td>
<td>Coralie</td>
</tr>
<tr>
<td>1109.69531</td>
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<td>18.00</td>
<td>-88.0</td>
<td>29.0</td>
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</tr>
<tr>
<td>1111.59481</td>
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</tr>
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<td>1112.62535</td>
<td>-60.03</td>
<td>12.00</td>
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</tr>
<tr>
<td>1113.67401</td>
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<td>7.00</td>
<td>-20.0</td>
<td>30.0</td>
<td>0.432</td>
<td>HARP5</td>
</tr>
<tr>
<td>1119.66549</td>
<td>90.12</td>
<td>10.00</td>
<td>1.0</td>
<td>10.0</td>
<td>0.800</td>
<td>FEROS</td>
</tr>
<tr>
<td>1121.59322</td>
<td>45.12</td>
<td>10.00</td>
<td>-10.0</td>
<td>11.0</td>
<td>0.919</td>
<td>FEROS</td>
</tr>
<tr>
<td>1179.50706</td>
<td>2.86</td>
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<td>29.0</td>
<td>0.482</td>
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<tr>
<td>1181.49387</td>
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<td>29.0</td>
<td>0.604</td>
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</tr>
<tr>
<td>1183.58674</td>
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<td>17.00</td>
<td>4.0</td>
<td>27.0</td>
<td>0.733</td>
<td>Coralie</td>
</tr>
</tbody>
</table>

$^a$ The zero-point of these velocities is arbitrary. An overall offset $\gamma_{rel}$ fitted separately to the data from three instruments has been subtracted.

$^b$ Internal errors excluding the component of astrophysical/instrumental jitter considered in Section 5.3.

The ZASPE code (see Chapter 3). ZASPE estimates the atmospheric stellar parameters and $v\sin i$ from high resolution echelle spectra via a least squares method against a grid of synthetic spectra in the most sensitive zones of the spectra to changes in the atmospheric parameters. ZASPE obtains reliable errors in the parameters, as well as the correlations between them by assuming that the principal source of error is the systematic mismatch between the data and the optimal
synthetic spectra. We used the new synthetic grid presented in chapter 2, and the spectral region considered for the analysis was from 5000 Å to 6000 Å, which includes a large number of atomic transitions and the pressure sensitive Mg II b lines. We obtained the following high precision parameters with ZASPE: $T_{\text{eff}} = 5840 \pm 91$ K, $\log g = 4.36 \pm 0.15$ dex, $[\text{Fe/H}] = -0.30 \pm 0.05$ dex and $v \sin i = 3.84 \pm 0.48$ km/s.

The resulting $T_{\text{eff}}$ and $[\text{Fe/H}]$ measurements were combined with the stellar density $\rho_\ast$ determined through our joint light curve and RV curve analysis, to determine the stellar mass, radius, age, luminosity, and other physical parameters, by comparison with the Yonsei-Yale (YY; Yi et al. 2001) stellar evolution models (see Figure 5.4). This provided a revised estimate of $\log g_\ast$, which was fixed in a second iteration of ZASPE. Our final adopted stellar parameters are listed in Table 5.4; the final atmospheric parameters are compatible to the ones obtained in the first ZASPE iteration. We find that the star HATS-17 has a mass of $1.131 \pm 0.03$ $M_\odot$, a radius of $1.091^{+0.070}_{-0.046} R_\odot$, and is at a reddening-corrected distance of 340 $^{+22}_{-17}$ pc.

We also carried out a joint analysis of the high-precision FEROS, CORALIE and HARPS RVs (fit using an eccentric Keplerian orbit) and the HS, PEST 0.3 m, LCOGT 1 m, and Swope 1 m light curves (fit using a Mandel & Agol 2002 transit model with fixed quadratic limb darkening coefficients taken from Claret 2004) to measure the stellar density, as well as the orbital and planetary parameters. This analysis makes use of a differential evolution Markov Chain Monte Carlo procedure (DEMCMC, ter Braak 2006) to estimate the posterior parameter distributions, which we use to determine the median parameter values and their 1σ uncertainties. The results are listed in Table 5.5. We find that the planet HATS-17b has a mass of $1.338 \pm 0.065$ $M_J$, and a radius of $0.777 \pm 0.056$ $R_J$. We also find that the observations are consistent with a circular orbit: $e = 0.029 \pm 0.022$, with a 95% confidence upper-limit of $e < 0.070$. Note, however, that due to the relatively long orbital period, and thus weak tidal interaction between the planet and
star, we do not fix the eccentricity to zero in the fit, as we often do for shorter period planets
where there is a prior expectation of the orbit being circular. The uncertainty in the eccentricity
thus contributes to the uncertainties of other parameters listed in Table 5.5.

In order to rule out the possibility that HATS-17 is a blended stellar eclipsing binary system, we
carried out a blend analysis of the photometric data following Hartman et al. (2012). We find
that all of the blend models considered provide a fit to the photometric data that has a higher
$\chi^2$ than the model consisting of a single star with a transiting planet, and that the best-fitting
blended eclipsing binary model can be rejected with 3σ confidence in favor of the single star
with a planet model. Moreover, the blend models which come closest to fitting the photometry
would have easily been detected as a composite system based on the spectroscopic observations
(RV and BS variations of several km s$^{-1}$). As is often the case, we find that while blends
involving stellar eclipsing binaries may be ruled out by the photometry, we cannot exclude the
possibility that HATS-17 is a transiting planet system diluted by light from an unresolved stellar
companion. We find that including a physical wide binary companion with a mass $M > 0.5 \ M_\odot$
leads to a slightly higher $\chi^2$, but all companions, up to the mass of HATS-17, are permitted
within 1σ. If HATS-17 has an unresolved stellar companion, the radius of HATS-17b could be
as much as 1.6 times larger than what we infer here (for the extreme case of a star of equal mass
to HATS-17).

Our analysis showed that HATS-17 is a relatively young (~2 Gyr) G-type star with physical
parameters very similar to the Sun, but with a substantial metal enrichment ([Fe/H]=+0.3). On
the other hand, HATS-17b is a weakly irradiated ($T_{\text{eq}} \sim 800$ K, $\langle F \rangle \sim 10^8$ erg s$^{-1}$cm$^{-2}$) Jovian
planet and due to its relatively long semi-major axis of ~0.13 AU it can be classified as a warm
Jupiter. One of the principal peculiarities of HATS-17b is that it has a very compact radius for
its Jupiter-like mass, yielding a very high density of $\rho_p=3.5$ g cm$^{-3}$ compared to Jupiter ($\rho_J=1.33$
Table 5.4: Stellar parameters for HATS-17.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
<th>Source</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>General properties</strong></td>
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<td></td>
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<tr>
<td>2MASS-ID</td>
<td>2MASS 12484555-4736492</td>
<td></td>
</tr>
<tr>
<td>GSC-ID</td>
<td>GSC 8249-00170</td>
<td></td>
</tr>
<tr>
<td>R.A. (J2000)</td>
<td>12h 48m 45.72s</td>
<td>2MASS</td>
</tr>
<tr>
<td>Dec. (J2000)</td>
<td>-47° 36' 49.3&quot;</td>
<td>2MASS</td>
</tr>
<tr>
<td>$\mu_{R.A.}$ (mas yr$^{-1}$)</td>
<td>-32.40±0.9</td>
<td>UCAC4</td>
</tr>
<tr>
<td>$\mu_{Dec.}$ (mas yr$^{-1}$)</td>
<td>7.5±1.4</td>
<td>UCAC4</td>
</tr>
<tr>
<td><strong>Spectroscopic properties</strong></td>
<td></td>
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</tr>
<tr>
<td>$T_{\text{eff}}$ (K)</td>
<td>5846±78</td>
<td>ZASPE</td>
</tr>
<tr>
<td>$[Fe/H]$</td>
<td>0.30±0.03</td>
<td>ZASPE</td>
</tr>
<tr>
<td>$v\sin i$ (km s$^{-1}$)</td>
<td>3.73±0.39</td>
<td>ZASPE</td>
</tr>
<tr>
<td>$\gamma_{RV}$ (km s$^{-1}$)</td>
<td>-22943.2±4.0</td>
<td>FEROS</td>
</tr>
<tr>
<td><strong>Photometric properties</strong></td>
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<tr>
<td>$B$ (mag)</td>
<td>13.105 ± 0.090</td>
<td>APASS</td>
</tr>
<tr>
<td>$V$ (mag)</td>
<td>12.39 ± 0.10</td>
<td>APASS</td>
</tr>
<tr>
<td>$g$ (mag)</td>
<td>12.665 ± 0.050</td>
<td>APASS</td>
</tr>
<tr>
<td>$r$ (mag)</td>
<td>12.162 ± 0.060</td>
<td>APASS</td>
</tr>
<tr>
<td>$i$ (mag)</td>
<td>12.08 ± 0.19</td>
<td>APASS</td>
</tr>
<tr>
<td>$J$ (mag)</td>
<td>11.082 ± 0.023</td>
<td>2MASS</td>
</tr>
<tr>
<td>$H$ (mag)</td>
<td>10.837 ± 0.022</td>
<td>2MASS</td>
</tr>
<tr>
<td>$K_s$ (mag)</td>
<td>10.698 ± 0.021</td>
<td>2MASS</td>
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<tr>
<td><strong>Derived properties</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>$M_\star$ ($M_\odot$)</td>
<td>1.131 ± 0.030</td>
<td>YY+\rho_\star+ZASPE</td>
</tr>
<tr>
<td>$R_\star$ ($R_\odot$)</td>
<td>1.091$^{+0.070}_{-0.046}$</td>
<td>YY+\rho_\star+ZASPE</td>
</tr>
<tr>
<td>$\log g_\star$ (cgs)</td>
<td>4.416 ± 0.042</td>
<td>YY+\rho_\star+ZASPE</td>
</tr>
<tr>
<td>$\rho_\star$ (g cm$^{-3}$)</td>
<td>1.38±0.27</td>
<td>YY+\rho_\star+ZASPE</td>
</tr>
<tr>
<td>$L_\star$ ($L_\odot$)</td>
<td>1.24±0.17</td>
<td>YY+\rho_\star+ZASPE</td>
</tr>
<tr>
<td>$M_V$ (mag)</td>
<td>4.57 ± 0.15</td>
<td>YY+\rho_\star+ZASPE</td>
</tr>
<tr>
<td>$M_K$ (mag,ESO)</td>
<td>3.08 ± 0.12</td>
<td>YY+\rho_\star+ZASPE</td>
</tr>
<tr>
<td>Age (Gyr)</td>
<td>2.1 ± 1.3</td>
<td>YY+\rho_\star+ZASPE</td>
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<td>$A_V$ (mag)</td>
<td>0.17 ± 0.11</td>
<td>YY+\rho_\star+ZASPE</td>
</tr>
<tr>
<td>Distance (pc)</td>
<td>339$^{+22}_{-16}$</td>
<td>YY+\rho_\star+ZASPE</td>
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Table 5.5: Orbital and planetary parameters for HATS-17b.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Light curve</td>
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</tr>
<tr>
<td>$P$ (days)</td>
<td>16.254611 ± 0.000073</td>
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<tr>
<td>$T_e$ (BJD)</td>
<td>2457139.1672 ± 0.0014</td>
</tr>
<tr>
<td>$T_{14}$ (days)</td>
<td>0.2011 ± 0.0038</td>
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<tr>
<td>$T_{12} = T_{34}$ (days)</td>
<td>0.0166 ± 0.0020</td>
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<tr>
<td>$a/R_*$</td>
<td>25.8$^{+1.1}_{-1.5}$</td>
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<tr>
<td>$\zeta/R_*$</td>
<td>10.83 ± 0.20</td>
</tr>
<tr>
<td>$R_p/R_*$</td>
<td>0.0726 ± 0.0026</td>
</tr>
<tr>
<td>$b^2$</td>
<td>0.187$^{+0.074}_{-0.083}$</td>
</tr>
<tr>
<td>$b = a \cos i / R_*$</td>
<td>0.432$^{-0.110}_{+0.079}$</td>
</tr>
<tr>
<td>$i$ (deg)</td>
<td>89.08 ± 0.26</td>
</tr>
<tr>
<td>Limb-darkening$^a$</td>
<td></td>
</tr>
<tr>
<td>$c_{1r}$</td>
<td>0.3640</td>
</tr>
<tr>
<td>$c_{2r}$</td>
<td>0.3272</td>
</tr>
<tr>
<td>$c_{1t}$</td>
<td>0.2710</td>
</tr>
<tr>
<td>$c_{2t}$</td>
<td>0.3370</td>
</tr>
<tr>
<td>RV parameters</td>
<td></td>
</tr>
<tr>
<td>$K$ (m s$^{-1}$)</td>
<td>99.1 ± 4.4</td>
</tr>
<tr>
<td>$e$</td>
<td>0.029 ± 0.022</td>
</tr>
<tr>
<td>RV jitter HARPS (m s$^{-1}$)</td>
<td>0.9 ± 4.1</td>
</tr>
<tr>
<td>RV jitter FEROS (m s$^{-1}$)</td>
<td>0.1 ± 9.3</td>
</tr>
<tr>
<td>RV jitter Coralie (m s$^{-1}$)</td>
<td>6 ± 13</td>
</tr>
<tr>
<td>Planetary parameters</td>
<td></td>
</tr>
<tr>
<td>$M_p$ ($M_\odot$)</td>
<td>1.338 ± 0.065</td>
</tr>
<tr>
<td>$R_p$ ($R_\odot$)</td>
<td>0.777 ± 0.056</td>
</tr>
<tr>
<td>$C(M_p, R_p)$</td>
<td>0.25</td>
</tr>
<tr>
<td>$\rho_p$ (g cm$^{-3}$)</td>
<td>3.50$^{+0.85}_{-0.51}$</td>
</tr>
<tr>
<td>log $g_p$ (cgs)</td>
<td>3.737$^{+0.060}_{-0.044}$</td>
</tr>
<tr>
<td>$a$ (AU)</td>
<td>0.1308 ± 0.0012</td>
</tr>
<tr>
<td>$T_{\text{eq}}$ (K)</td>
<td>814 ± 25</td>
</tr>
<tr>
<td>$\langle F \rangle$ (10$^7$ erg s$^{-1}$ cm$^{-2}$)</td>
<td>9.9 ± 1.3</td>
</tr>
</tbody>
</table>
5.4 Discussion

In this Chapter we have presented the discovery of HATS-17b, the first transiting warm Jupiter of the HATSouth survey and the transiting extrasolar planet with the longest orbital period detected to date by a ground-based photometric survey. The left panel of Figure 5.5 shows that HATS-17b, with its period of 16.25 days, lies in a sparsely populated region of the parameter space of confirmed transiting extrasolar giant planets \((M_p > 0.25 M_J, R_p > 0.5 R_J)\) that have measured masses and densities. There are only 19 confirmed giant planets with longer orbital periods, with most of them (17) discovered by the space-based missions Kepler and CoRoT, and orbiting stars that are generally too faint for performing detailed follow-up observations to further characterize those systems. In fact, the masses of ten of the long period planets discovered from space were determined by transit timing variations (TTVs) because it was easier than obtaining precise RV measurements of their faint host stars. HATS-17b, on the other hand, has a bright \((V = 12.4)\) host which allowed a detailed determination of the orbital parameters of the system via RV measurements and can be the target of future spectroscopic and photometric follow-up.

Due to its relatively large semi-major axis \((a \approx 0.13 \text{ AU})\), HATS-17b is a low irradiated planet. The flux received per unit area by the planet is \(\langle F \rangle = 9.9 \times 10^7 \text{ erg cm}^{-2} \text{s}^{-1}\), which is low enough that we do not expect heating from the star to significantly impact the structure of the planet (Kovács et al. 2010; Demory & Seager 2011). The right panel of Figure 5.5 shows that there are \(\sim 30\) other well characterized giant planets with \(\langle F \rangle < 2.0 \times 10^8 \text{ erg cm}^{-2} \text{s}^{-1}\) that belong to the mentioned group, with 11 of them discovered by ground-based transit surveys orbiting stars at shorter semi-major axes than HATS-17b but around less luminous host stars than HATS-17. In addition to the low insolation level of HATS-17b, the low eccentricity of its orbit ensures that tidal interactions with the star are not able to generate internal heating on the planet. This
particular state of HATS-17b is not applicable for the whole group of low irradiated planets as many of them have measurable eccentricities that could generate tidal heating during periastron passages.

Transiting systems like HATS-17b, in which we can isolate the planetary physical properties from significant heating mechanisms produced by the stellar host, are very important for constraining theoretical models of the structure of giant planets. In Figure 5.6, the physical properties of HATS-17b are contrasted with the ones of the rest of the well characterized transiting giant exoplanets. Both panels illustrate that HATS-17b is a peculiar object regarding its structure. HATS-17b possesses a radius of $R_p=0.777\,R_J$ which is extremely compact even for low irradiated planets. The planet that most closely resembles HATS-17b is WASP-59b (Hébrard et al. 2013) with $R_p=0.78\,R_J$, $M_p=0.86\,M_J$, and $\langle F \rangle = 4.5 \times 10^7\,\text{erg cm}^{-2}\,\text{s}^{-1}$. The rest of the planets that share a similar radius have masses smaller than 0.4 $M_J$. The compact nature of HATS-17b is further illustrated in the right panel of Figure 5.6, where it stands out as the densest giant planet with masses $M_p<2\,M_J$.

The small radius of HATS-17b is in concordance with the low irradiation levels of warm Jupiters. However, its particular value is not straightforward to explain with standard theoretical models of planetary structure. Figure 5.7 shows that, for the stellar and planetary properties of the HATS-17 system, the Fortney et al. (2007) models for giant planets predict a radius that is more than $3\sigma$ larger than the observed one even for the maximum available core mass of $100\,M_\oplus$. By performing an extrapolation of these models we have estimated that a central core of $\sim 200\,M_\oplus$ is required to explain the compact nature of HATS-17b. Such a massive core implies that $\sim 50\%$ of the planet mass is composed of heavy elements, which strongly contrasts with the $\sim 10\%$ we can infer from Jupiter given a $\sim 15\,M_\oplus$ core (Militzer et al. 2008) and is closer to the fraction of heavy elements predicted for the solar system ice giants.
The massive core inferred for HATS-17b can be linked to the high metallicity of the parent star ([Fe/H]=+0.3 dex). In the context of the core accretion scenario of giant planets formation, a more metal rich disk can be more efficient in forming massive cores. Several works (Guillot et al. 2006; Burrows et al. 2007; Miller & Fortney 2011) have claimed to find a correlation between the stellar metallicity and the amount of heavy elements inferred for giant TEPs. In particular, Miller & Fortney (2011) (hereafter M11) find that for low irradiated planets there is a minimum core mass of $\sim 10 M_\oplus$ and that from this value the amount of heavy elements present in the planets’ interior raises as a function of [Fe/H], with CoRoT-10b (Bonomo et al. 2010) being the most extreme case with a heavy element content of $M_\text{t}=182\pm 94 M_\oplus$ and [Fe/H]=+0.26 dex. The left panel of Figure 5.8 shows this claimed correlation for the 14 systems analyzed by M11 and adding HATS-17b. HATS-17b seems to agree quite well with the correlation proposed by M11. Even though the predicted heavy element content for a metallicity of [Fe/H]=+0.3 dex should be closer to $\sim 100 M_\oplus$, the dispersion of the correlation is greater than the individual errors. Clearly, detections of more warm giant TEPs are required.

M11 also proposed a negative correlation between the metal enrichment of the planet relative to the star and the mass of the planet. This correlation is observed in the giant planets of our solar system where Uranus and Neptune are more enriched in heavy elements than Saturn and in turn Saturn is more metal enriched than Jupiter. The right panel of Figure 5.8 shows that HATS-17b seems to subtly depart from this correlation having enrichments similar to Saturn mass planets rather than the ones of Jupiter mass planets.

In summary, the massive core of HATS-17b can be expected given the high metallicity of the parent star, but it seems to lack a more extended H/He envelope. The mechanism that allows the formation of such massive embryos is unclear. If HATS-17b was formed by core accretion at $a = 5$ AU and we assume that the total heavy element composition of HATS-17 scales with the
iron abundance, we can infer an embryo of $M_c = 30 M_\oplus$, which corresponds to just 15% of the estimated mass of the core of HATS-17b. More massive cores can be formed at larger distances but even if the primordial material is available, the planetesimal accretion rate must exceed the gas accretion rate which should be difficult to accomplish for cores with $M_c > 20 M_\oplus$. An alternative explanation for the extremely massive core of HATS-17b can be related to collisions with other objects in the system posterior to the dispersal of the protoplanetary disk. Liu et al. (2015) proposed, based on numerical simulations, that giant impacts of super-Earth-like planets or mergers with other gas giants generally leads to a total coalescence of impinging gas giants and that sometimes the collisions can disintegrate the envelope of gas giants which may also explain the seeming lack of a massive H/He envelope for HATS-17b. This hypothesis is further supported by the study of Petrovich et al. (2014) which determined that at small semi-major axes ($a < 0.5$ AU), gravitational interactions between planets in unstable systems mostly lead to collisions rather than excitation of highly eccentric and inclined planetary orbits.

A more detailed modelling of the structure of HATS-17b, in which the solid material is distributed through the entire envelope of the planet and not only in a central core, can also lower the amount of heavy elements required to explain its small radius. For example, in the case of the massive planet CoRoT-20b (Deleuil et al. 2012, $M_p = 4.24 M_J$), the inclusion of the Baraffe et al. (2008) calculations can decrease by a factor of three the 800 $M_\oplus$ in heavy elements that were initially estimated for this planet.

The current orbital distance of HATS-17b from its host star is compatible with migration via angular momentum exchange with the protoplanetary disk. Migrations through gravitational interactions with other planetary and/or stellar companions should excite the eccentricity of the system and then tidal interactions with the star during periastron passages would be responsible
of decreasing the semi-major axis and circularising the orbit. The eccentricity of HATS-17b is consistent with $e = 0$, while being too far away from it parent star to have suffered from significant tidal interactions. On the other hand, disc migration is expected to suppress any initial eccentricity of giant planets (Dunhill 2015). While disk migration stands up as the most probable origin for the current semi-major axis of HATS-17b, high eccentricity migration mechanisms cannot be totally discarded. Kozai-Lindov oscillations (Kozai 1962) produced by interactions with a distant stellar companion (Takeda & Rasio 2005) or with a closer planetary companion (Naoz et al. 2011) can be taking place but we may be just observing a stage of low eccentricity in the cycle. Long term RV monitoring of HATS-17b can unveil the presence of another object in the system and measurements of the Rossiter-McLaughlin effect can detect inclinations in the orbit of HATS-17b produced by the interaction with the companion. However, Dong et al. (2014) predicts that non-eccentric warm Jupiters probably present well aligned orbits with the spin of the star.

As is evident from the previous paragraphs, HATS-17b belongs to a group of exoplanets that are useful for constraining theories of structure and evolution of giant planets, but which has a low number of well characterized systems discovered to date. The detection of these transiting warm Jupiters around bright stars is fraught with several difficulties due to the low transit probability of long period planets, low occurrence rate of giant planets with respect to terrestrial planets, and the limited duty cycle that one site ground-based transit surveys are affected by. Moreover the confirmation of the planetary nature of transiting warm Jupiter candidates requires extensive spectroscopic and photometric follow-up campaigns in which observations must be spread over many more epochs compared to the follow-up observations required to confirm short period planets. Taking advantage of its three observing sites in the southern hemisphere, separated by almost 120 deg in longitude each, the HATSouth survey can better tackle these difficulties, and
HATS-17b is a testament to its capabilities.
Figure 5.3: Top panel: High-precision RV measurements from the MPG 2.2 m/FEROS, the ESO 1.2 m/CORALIE, and the ESO 3.6 m/HARPS instruments, together with our best-fit orbit model. Zero phase corresponds to the time of mid-transit. The center-of-mass velocity has been subtracted. Second panel: Velocity $O-C$ residuals from the best-fit model. The error bars for each instrument include the jitter which is varied in the fit. Third panel: Bisector spans (BS). Note the different vertical scales of the panels.
Figure 5.4: Comparison between the measured values of $T_{\text{eff}}$ and $\rho_*$ (from ZASPE applied to the FEROS spectra, and from our modeling of the light curves and RV data, respectively), and the $Y^2$ model isochrones from Yi et al. (2001). The best-fit values (dark filled circle), and approximate 1$\sigma$ and 2$\sigma$ confidence ellipsoids are shown. The values from our initial ZASPE iteration are shown with the open triangle. The $Y^2$ isochrones are shown for ages of 0.2 Gyr, and 1.0 to 14.0 Gyr in 1 Gyr increments.
Figure 5.5: Left panel: V magnitude of the discovered transiting giant planets ($M_p > 0.25M_J$, $R_p > 0.25R_J$) as function of their orbital periods. TEPs discovered by ground-based transit surveys correspond to the gray circles, while RV discovered transiting planets are shown in yellow circles. TEPs discovered from space are shown in orange. Circles correspond to the planets for which the masses determination were performed via RV measurements while squares are used to identify systems for which the masses were estimates with TTVs. The black circle with a cross shows the position of HATS-17b which lies in a sparsely populated region of the parameter space and stands out as the TEP with the longest orbital period discovered to date by a ground-based transit surveys. Right panel: Radii of TEPs as function of the incoming flux per unit area in the surface of the planet. The symbols and colours represent the same features as in the left panel. The vertical dashed line marks the insolation level below which extra heating mechanisms do not produce inflated giant planets. HATS-17b lies in the zone of weakly irradiated planets.
Figure 5.6: Left panel: mass-radius diagram of the detected giant TEPs. Black circles are planets with insulation levels greater than $\langle F \rangle < 2.0 \times 10^8$ erg cm$^{-2}$s$^{-1}$, while orange circles correspond to planets receiving low irradiation. HATS-17b present one of the smallest radii among transiting giant planets. Right panel: density of giant planets as function of the planetary mass. HATS-17b lies at the upper envelope of this distribution.
Figure 5.7: Evolution models of the radius of a planet as a function of age for the planetary and stellar properties of the HATS-17 system. The solid lines represent models with central core masses of 10, 25, 50 and 100 $M_{\oplus}$ from Fortney et al. (2007). The dashed line corresponds to an extrapolation of the models for a core mass of 200 $M_{\oplus}$. The filled circle corresponds to HATS-17b. A very high content of solid material is required to explain the compact radius of HATS-17b.
Figure 5.8: Left: Correlation between the mass of the heavy elements in weakly irradiated planets and the metallicity of the host star. The gray circles correspond to the values found by Miller & Fortney (2011) and the orange circle represents HATS-17. The massive core of HATS-17b can be related to the high metallicity of its host. Right: Negative correlation proposed by Miller & Fortney (2011) between the metal enrichment of the planets with respect to the metal enrichment of the star as a function of the mass of the planet. In this case HATS-17b tends to depart from the correlation and seems to lack of a massive H/He envelope for its given mass.
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Chapter 6

Conclusions and Future work

6.1 Summary

In this thesis I have presented the core of the work that I have carried out during my PhD, which had a large focus on the development of computational tools for the processing and analysis of spectroscopic data that were used to perform the spectroscopic follow-up of TEP candidates from the HATSouth survey.

In Chapter 2, I have described the CERES system which is a set of routines written for the reduction and processing of echelle spectrograph data. The main purpose of these routines is the creation of fully automated pipelines that are able to process the data from scratch in a homogeneous and robust manner. CERES has been already applied to generate pipelines for 10 instruments. These pipelines perform typical CCD reduction steps, determination and tracing of the echelle orders, optimal extraction of the science frames, computation of the wavelength solution using ThAr lamps and/or Fabry-Perot systems, estimation of radial velocity (RV) and bisector span (BS) measurements and a rough spectral classification. These pipelines have been used
to process HATSouth follow-up data acquired with the FEROS, Coralie, DuPont and HARPS instruments and the results obtained have allowed the identification of an important fraction of false positives and the confirmation of the planetary nature of \( \approx 50 \) TEPs. Moreover, these pipelines have been successfully used to process data for other projects with different scientific goals (e.g. characterisation of eclipsing binaries, discovery of RV exoplanets, identification of supernova progenitors and characterisation of novae).

In Chapter 3, I have presented ZASPE which is a new algorithm for the precise computation of atmospheric stellar parameters from high resolution echelle spectra. ZASPE was developed in order to analyse spectra of the stellar hosts of the TEPs discovered by the HATSouth survey. ZASPE obtains the atmospheric parameters by applying an iterative least square minimisation routine using a grid of synthetic spectra. The comparison is only performed in the most sensitive zones present in wavelength range observed to changes in the atmospheric parameters. The main novelty of our algorithm is that the estimated uncertainties include the systematic mismatch between the observed spectrum and the best fitted synthetic one and the complete covariance structure is obtained after a Monte Carlo process in which the depths of the absorption lines are randomly modified according to the distribution of mismatches determined from the observed and synthetic spectra. In the development of ZASPE we proved that publicly available grids of synthetic spectra must be used with caution in the estimation of precise atmospheric parameters. We found that the results obtained with the grids of Coelho et al. (2005) and Husser et al. (2013) present some important systematic trends and biases if compared with reference values. We generated our own grid based on the ATLAS9 model atmospheres which was extensively validated with a set of FEROS spectra of stars that were analysed by SWEET-Cat (Santos et al. 2013). One of the most important conclusions of the performance of ZASPE is that we obtain uncertainties and correlations that are in line with the expected level of systematic uncertainties based on studies that have analysed spectra of a sample of stars with different methods.
In chapter 4, I have reported the discovery of HATS-9b and HATS-10b, which are two transiting hot Jupiters that lie in one of the fields of the K2 mission. In particular HATS-9b lies in a working silicon and will be observed by the K2 mission (EPIC217671466), allowing to characterise this planet in great detail. Both planets are rather compact for their relatively high insolation levels, which could be partially explained by the metal richness of their parent stars. Another explanation for the small radius of HATS-9b may be linked to the advanced age of the system (~10.8 Gyr).

Finally, in chapter 5, I have reported the discovery of HATS-17b, which is the first warm Jupiter discovered by the HATSouth survey and by far the TEP with the longest period discovered by a ground based photometric survey. HATS-17b is a Jupiter-mass planet with a very compact radius of 0.777 \( R_J \), which translates in to a very massive central core if standard theoretical models of planetary structure are used. This massive solid core seems to be expected given the high metallicity of HATS-17 ([Fe/H]=0.3) and agrees with the correlation found by Miller & Fortney (2011).

### 6.2 Conclusions

The HATSouth survey is entering a phase of continuous discoveries of TEPs. This goal has been achieved thanks to a collaborative effort of many researchers, who have been involved in the project by performing different tasks including the construction and installation of the 3 HATSouth stations, the development of the control system to robotise and automatise the 6 HATSouth units, the development of reduction routines to convert the numerous raw images in to photometric light curves, the identification of TEP candidates, the development of ex-
tensive photometric and spectroscopic follow-up campaigns and the final analysis of the new exoplanetary systems. Even though each of these steps is required for successfully arriving to a new TEP detection, this HATSouth pipeline was presenting two important bottlenecks that were preventing the confirmation of most of the candidates.

The first bottleneck was related to the RV monitoring of the candidates. Almost all of the ~50 confirmed HATSouth TEPs rely on FEROS observations to obtain their masses and orbital parameters, however, the official FEROS pipeline was unable to deliver RVs with the precision required to confirm their planetary nature. In this context, the development of the pipeline built from the CERES routines was a fundamental tool that enabled us to confirm the numerous Jupiter and Saturn mass candidates and also enlarge our list of strong Neptune mass candidates.

The second bottleneck was the absence of a dedicated procedure to estimate the atmospheric parameters in a homogeneous manner in which the correlations between the parameters were computed to be used as input in the global MCMC analysis. For the first 8 published HATSouth TEPs, different standard routines (SPC and SME) were used to compute the atmospheric parameters but they did not deliver the covariance matrix of the obtained parameters and in fact the uncorrelated errors that were reported were not directly computed from the data. Instead, given that the errors were expected to be governed by systematics, an arbitrary typical uncertainty was considered. The development of ZASPE was able to take all these weakness of the other routines into account and is currently the standard spectral analysis routine of HATSouth stellar hosts.

Thanks in part to the development of CERES and ZASPE, the HATSouth survey has started this year (2015) to achieve its primary goal which is the detection of TEPs amenable for further characterisation in sparsely populated regions of the parameter space. In the beginning of the year the announcement of HATS-6b caused an important impact because it was one of only
four giant planets known to have stellar hosts with masses $M_* < 0.6 \, M_\odot$, challenging theories of planetary formation around low mass stars. After that, during midyear we reported the discovery of the transiting super-Neptunes HATS-7b and HATS-8b. Only a handful of well characterized TEPs have masses in the range between Neptune and half the one of Saturn and these objects are required for testing theories of the formation of giant planets which claim the existence of a pause of this kind of systems due to the runaway growth that is triggered when the planetary embryo becomes massive enough. Finally, at the end of the year, we have reported the discovery of HATS-17b which is the TEP with the longest period discovered from the ground and can be used for testing theories of migration and structure of giant extrasolar planets, because it lies sufficiently far away from its host star to suffer from strong tidal interactions that modify the orbital geometry and be subject also to low enough irradiation levels, which allows us to neglect the unknown inflation mechanism close in giant planets are victims of.

6.3 Ongoing and future work

The HATSouth survey is an ongoing project that is expected to significantly increase the number of TEPs amenable for characterisation. The computational routines developed in this thesis will be certainly used to make these detections possible. However, there are some pending issues regarding the topics presented in the previous chapters that can be improved in the future. In the context of the echelle pipelines a major upgrade will be the development of a set of routines for the computation of precise RVs with the $I_2$ (iodine) cell technique. The principal action items in this regard will be to obtain the spectra of the $I_2$ cell for each of the instruments and the development of the deconvolution routine. Other possible action items are the improvement of the existing pipelines via the inclusion of new observing modes and the processing of more detectors; and also the development of pipelines for other instruments. In this regard, it is expected
that the official pipeline of the new FIDEOS spectrograph, to be installed at the 1m telescope in La Silla Observatory, will be based on the CERES system. Finally, the principal upgrade for ZASPE will be the inclusion of the analysis of stars with $T_{\text{eff}} < 4000K$. The principal limitation for adapting ZASPE to process spectra of M-dwarfs is that this type of stars presents numerous absorption bands in which case the typical mismatch effects can no longer be modelled as single multiplicative factors that modify the depth of the zones. A more detailed modelling framework of the mismatch structure will be required and we will develop such a framework in the future.

One particular imminent upgrade of the HATSouth project, in which I will be involved in the following months, will be the installation and commissioning of CHAT (standing for the Chilean-Hungarian Automated Telescope). It will be a 0.7m robotic telescope located in Las Campanas Observatory and will be mostly dedicated to the photometric follow-up of HATSouth candidates, allowing the fast rejection of false positives, which will translate in to a more efficient use of our granted observing time with spectroscopic facilities. This upgrade is expected to boost our number of discovered planets and also increase the speed of the confirmation process.

Another interesting project that will focus my efforts in the near future will be the development of the HATPI instrument, which will consist of 63 lenses of 6.7cm aperture that will survey the complete sky above 30 deg with a cadence of 30s. This instrument will be also installed in Las Campanas Observatory and will be able to detect a great deal of bright transient and variable phenomena, including small TEPs around bright stars.

Finally, all the machinery presented in this thesis can be applied to the follow-up and characterisation of TEP candidates of current and future space-based missions. As an example, our team at PUC has identified multiple candidates from the K2 campaigns 4 and 5, that can be observed from the southern hemisphere. We have started a follow-up campaign for the strongest candidates using the CORALIE, FEROS and HARPS spectrographs, with the data being processed
through CERES and ZASPE. Figure 6.1 shows the phase-folded K2 detection light curve and HARPS follow-up RVs for CL005b (internal name, Brahm et al. 2016, in prep). A preliminary analysis of the data points towards a 0.44$M_J$, 1.25$R_J$ inflated hot Saturn in a 4.1 days circular orbit around a $V = 13$ star. The atmospheric parameters of the host star reported by ZASPE are $T_{\text{eff}}=5492 \pm 80$ K, $\log g=4.56 \pm 0.09$, $[\text{Fe/H}]=0.04 \pm 0.04$ dex and $v \sin i=3.35 \pm 0.4$ km s$^{-1}$.

![Graph](image)

**Figure 6.1:** The top panel shows the phase-folded, long cadence K2 data (gray points) for a hot Jupiter candidate from K2 and the best fit of the transit (red line), while the bottom panel shows the follow-up RVs that confirm the planetary nature of the candidate.
Chapter 6. Conclusions

This and other K2 candidates will function as our training set for the Transiting Exoplanet Survey Satellite (TESS, Ricker et al. 2014) mission, which will discover thousands of TEPs around bright stars that will require detailed spectroscopic follow-up observations. The systems that will be discovered by TESS, K2 and HATPI, and confirmed through our efforts, should certainly allow us to gain a deeper understanding on the physical processes that govern the formation and evolution of extrasolar planetary systems.
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