FACULTY
OF MATHEMATICS
AND PHYSICS
Charles University

HABILITATION THESIS

Petr Kabáth

Efficient ground-based follow-up for exoplanetary space missions

Astronomický ústav AV ČR, v. v. i.

Prague 2023

I declare that I carried out this habilitation thesis independently, and only with the cited sources, literature and other professional sources. It has not been used to obtain another or the same degree.

I understand that my work relates to the rights and obligations under the Act No. 121/2000 Sb., the Copyright Act, as amended, in particular the fact that the Charles University has the right to conclude a license agreement on the use of this work as a school work pursuant to Section 60 subsection 1 of the Copyright Act.

In .... date ....

Author's signature

I would like to thank my colleagues who supported my work through most of almost two decades. I am grateful to my students and students from the partner institutes without whom I would not have been able to publish some of the papers. My thanks goes to Thomas Fruth, Jiří Žák, Claudio Caceres and Silvia Sabotta. I am thankful to David Vokrouhlický who provided me with useful comments for the thesis. I have always enjoyed our discussions with Valentin Ivanov. To Henri Boffin I am grateful for his enthusiasm, inspiration and for our numerous discussions, not only regarding exo-atmospheres. Henris support was crucial for the founding of the exoplanetary group in Ondřejov. At the Astronomical institute, my thanks goes to Petr Heinzel for his support. Furthermore, I very much appreciate a great feedback, help, and support of Marek Skarka and Ján Šubjak.

However, all this work could not have happened without support of my family. Especially, I am very grateful for support and patience of my wife Martina to whom I wish to dedicate this thesis.

Title: Efficient ground-based follow-up for exoplanetary space missions

Author: Petr Kabáth

Stelární oddělení: Astronomický ústav AV ČR, v. v. i.

Abstract: New exoplanets are reported at a rapid pace thanks to observations, initially from the *Kepler/K2* and now from the *TESS* space missions. The *TESS* mission is almost covering the whole sky with high photometric precision allowing the detection of thousands of planets from super-Earth to Jupiter sizes. However, the detection of such transit candidates is only the beginning of a greater story. After identifying the promising light curve, a whole machinery of ground-based follow-up observations is crucial to confirm or reject the new exoplanetary candidate. The initial screening, which aims at determining the stellar hosts parameters and investigating the probability of false positive detection, consumes several hours of telescope time. The subsequent step of measuring the radial velocities to precisely determine the mass and radius of the new exoplanet candidate from the combined spectroscopic and photometric data can take dozens of hours of telescope time. Therefore, 2-m telescopes with precise spectrographs and an efficient organisation of follow-up observing programs are crucial for the success of space missions. In this work, we present results and developments from the early days of planetary space missions – *CoRoT* – to the current era of large data sets arising from the *TESS* mission. We present the resurrection of the OES spectrograph at the Perek 2-m telescope located in Ondrejov, Czechia. We highlight our results with the OES spectrograph in the context of ground-based follow-up. Furthermore, we discuss the role of the precise instrumentation at 2-m class telescopes for the further characterisation of exoplanets and perhaps even their atmospheres. Finally, an outlook for the upcoming *PLATO* era is presented with a brief description of the new instrumentation project.

Keywords: exoplanets instrumentation: spectroscopic instrumentation: photometric

Contents

1. Introduction

The detection of exoplanets is a very dynamically evolving research topic. However, the first foundations in the relatively modern era were described by Otto Struve, who calculated the impact of a substellar object on the radial velocities of their host star [Struve, 1952]. Later, the first spectroscopic surveys with an aim to detect extrasolar planets were designed. New methods using thermally stable spectrographs, gas-filled cells and telluric lines were introduced to push down the accuracy of the measurements into the m/s domain Griffin [1973], Campbell & Walker [1979]. The story of exoplanetary research is nowadays the story of large survey programs monitoring the sky with very high precision in photometric and spectroscopic measurements.

One of the first reported exoplanetary candidate, gamma Cephei A b [Campbell et al., 1988] - was retracted in 1992 Walker et al. [1992] because of concerns regarding the instrument capabilities. This story illustrates the challenges in the planetary validation process. The science validation of planetary candidates is a complex process which requires various instrumentation and a combination of photometric and spectroscopic devices. The Gamma Cephei planet was in fact confirmed by Hatzes et al. [2003b] who measured a mass of $1.7\,\mathrm{M_{Jupiter}}$ and an orbital period of 906 days. The semi-amplitude of radial velocity variations of the host star due to the planet Gamma Cephei Ab was reported as 27 m/s[1]. There were also other reports of planets such as ”Dave Latham‘s” substellar object reported in 1989 [Latham et al., 1989]. Thanks to recent *GAIA* data, this object turned out to be more likely a star with a stellar companion with low mass or a brown dwarf but not a planet [Kiefer, 2019].

We note also the pulsar planets detection for sake of completeness [Wolszczan & Frail, 1992]. Planetary systems around pulsar stars are interesting class of objects detected by the pulsar delays of the system due to a planet. It is not clear whether they formed only after the death of the star and its transformation to a pulsar or whether the remnants of an existing planetary system survived the death of the star [Wang et al., 2006]. However, these very interesting objects are in different category as we are focusing this thesis on planets around main sequence stars. The limitation of the available instrumentation is one of the main drivers for the exoplanetary research. Pushing down the spectroscopic precision in radial velocities reveals smaller and smaller planets. Furthermore improving of the accuracy of spectroscopic instruments allows for characterisation and description of the planetary environments. Nowadays, the potential of instrumentation measuring the radial velocities is at the level of cm/s (accuracies) [Pepe et al., 2021] and photometric surveys will reach down to 10 parts per million (ppm) with *PLATO*[2] space mission.

The first confirmed planet 51 Peg b came in 1995 and it changed our thinking of the Universe [Mayor & Queloz, 1995]. This gas giant was orbiting its solar-like star in only 4.2 days! How could such a planet evolve so close to its star? Is such a configuration common in the Universe? And what about our Solar system: is

---

[1] The radial velocity semi-amplitude due to Gamma Cephei Ab is about a half of the semi-amplitude for 51 Pegasi b discovered in 1995.

[2] https://sci.esa.int/s/8rPyPew

it unique? These questions arose immediately with the first confirmed exoplanet and we are trying to answer them step-by-step. Furthermore, this ground breaking discovery was made with the ELODIE spectrograph [Baranne et al., 1996] installed at the 1.92-m telescope from Observatoire de Haute Provence, stressing the role mid-sized-aperture telescopes play.

Nowadays, we know that to detect and subsequently characterise exoplanets, especially the small ones, a well-coordinated collaboration between space and ground is required. The first transit of an exoplanet was detected in 1999 by Charbonneau et al. [2000] and Henry et al. [2000] by the small aperture ground-based TrES (Trans-Atlantic Exoplanet Survey) telescope [Alonso et al., 2004]. This set course for new survey projects seeking for exoplanetary signatures from ground but also from space. The first ground-based surveys were WASP [3], which is still the most successful survey, HAT, now HATNet [4] were later followed by many other projects. The geometric probability of a transit of a hot Jupiter - an exoplanet of a size of a Jupiter close to its host star - is about 10 %. We are starting to learn that large gas giants are less frequent than small rocky planets [Bayliss & Sackett, 2011, Bashi et al., 2020], at least on short orbits. Therefore, it is clear that a huge amount of stars needs to be observed to detect a gas giant from the ground. Gas giants present typically a brightness decline up to a few percent, however a small planet would show a brightness decline in parts-per-million. The size of the star plays its role too, of course.

Small planets are typically very challenging for detection with ground-based surveys. Therefore, we had to start transit surveys in space: the first of its kind was *CoRoT*, launched in 2006 [Auvergne et al., 2009]. The *CoRoT* space mission was a French-led ESA mission, consisting of a small telescope with a mirror of 27 cm and with an array of CCDs dedicated to exoplanet and asteroseismology programs. The *CoRoT* mission had installed prisms to separate the different colors of light in order to characterise the stellar variability [Moutou et al., 2013]. However, such feature made the stellar Point-Spread-Function (PSF) too broad and thus data suffered by contamination from nearby stars.

The next space mission dedicated to exoplanet research was NASA *Kepler* mission launched in 2009 [Borucki et al., 2010]. The *Kepler* mission had a primary mirror of 1.4 m therefore opening an unprecedented window in the photometric precision. The mission delivered many candidates and planets, also later from the continuation of *Kepler*, the *K2* mission [Borucki et al., 2011, Howell et al., 2014]. Furthermore, we acquired knowledge on the statistical distribution of different types of planets [Howard et al., 2012, Buchhave et al., 2012]. However, the strategy of staring at one selected field for a few years had its toll. Many *Kepler* targets and candidates for exoplanets were very faint and impossible to follow-up from the ground.

However, a new NASA mission *TESS* was launched in 2019 [Ricker et al., 2015]. The *TESS* mission is designed to survey about 85% of the sky. It is observing a core sample of 200,000 stars and it was already extended with further extensions planned. The *TESS* mission consists of four camera lenses of 10-cm diameter each. The photometric accuracy should be sufficient to detect the Super-Earth planets around dwarf stars. However, the angular resolution of the *TESS*

---

[3] https://www.superwasp.org

[4] https://hatnet.org

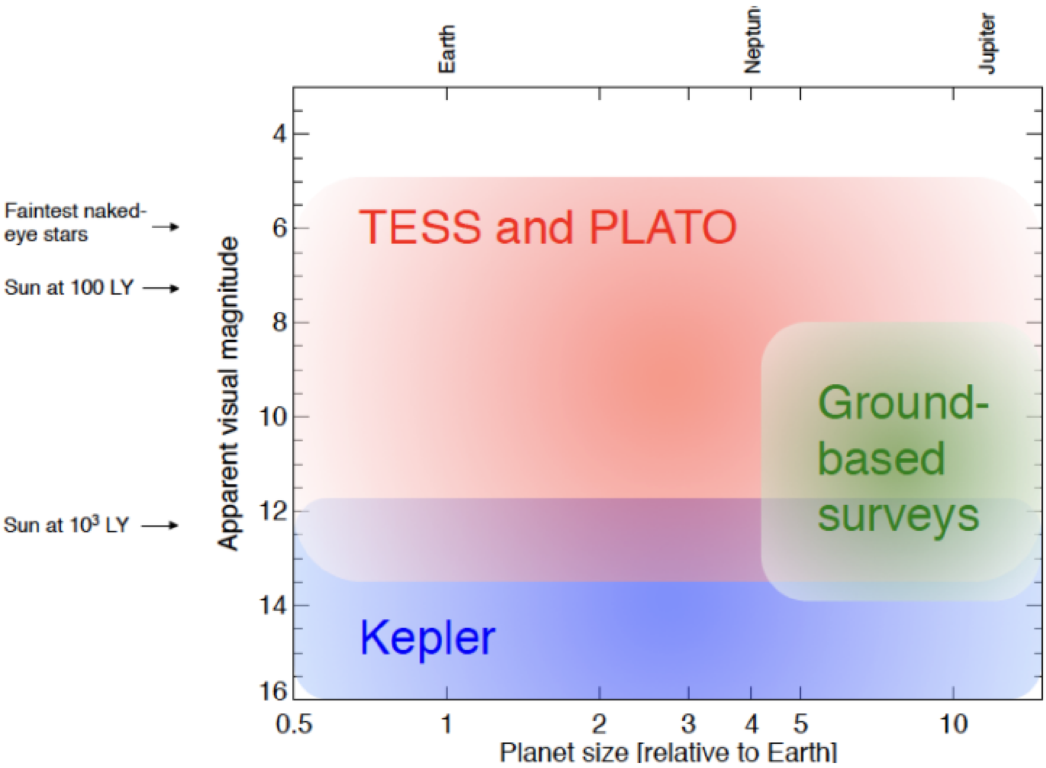

Figure 1.1: Comparison of the *Kepler* and the *TESS* mission in terms of stellar brightness of target sample. Fig. from [Heng & Winn, 2015].

mission is about 21 arcsec which is much larger than 4 arcsec of *Kepler* [Gilliland et al., 2011]. Therefore, the *TESS*mission requires the ground-based follow-up even more to distinguish the candidates from false positives and a few expectation before the mission launch were described e.g. here Sullivan et al. [2015].

The *PLATO* mission will be launched in 2027 and it will consist of 26 cameras monitoring 2200 degrees^2 on sky and it is designed, among many other goals, to detect the Earth analogue around Sun-like star [Rauer et al., 2014]. All from about a million stars from core sample will be in the range of $V = 4 - 11$ mag thus making them suitable for the ground-based follow-up. The difference between mission concepts is clearly demonstrated in Fig. 1.1.

The ground-based follow-up, spectroscopic and photometric, is essential to characterise the new candidates, due to the relatively large false positive rates which were up to 40 % for certain type of planets Fressin et al. [2013]. Without spectroscopy, we are not able to determine precise stellar parameters, such as effective temperature T_{eff}, the metallicity [Fe/H], the projected rotational velocity $v \sin i$ and the surface gravity $\log(g)$. Without precise stellar parameters, we can not determine the planetary radius. In addition, without spectroscopic determination of precise radial velocities of exoplanetary candidates host stars, the precise mass determination is not possible. Spectral parameters can be typically obtained also for fainter stars, however, precise radial velocities can be measured only for brighter stars (roughly up to $V = 14$ mag depending on the instrument and telescope). Therefore, most of the faint candidates from the *Kepler* mission do not have precise masses and radii as the precise radial velocities were impossible to obtain. The problem of determination of mass and radius

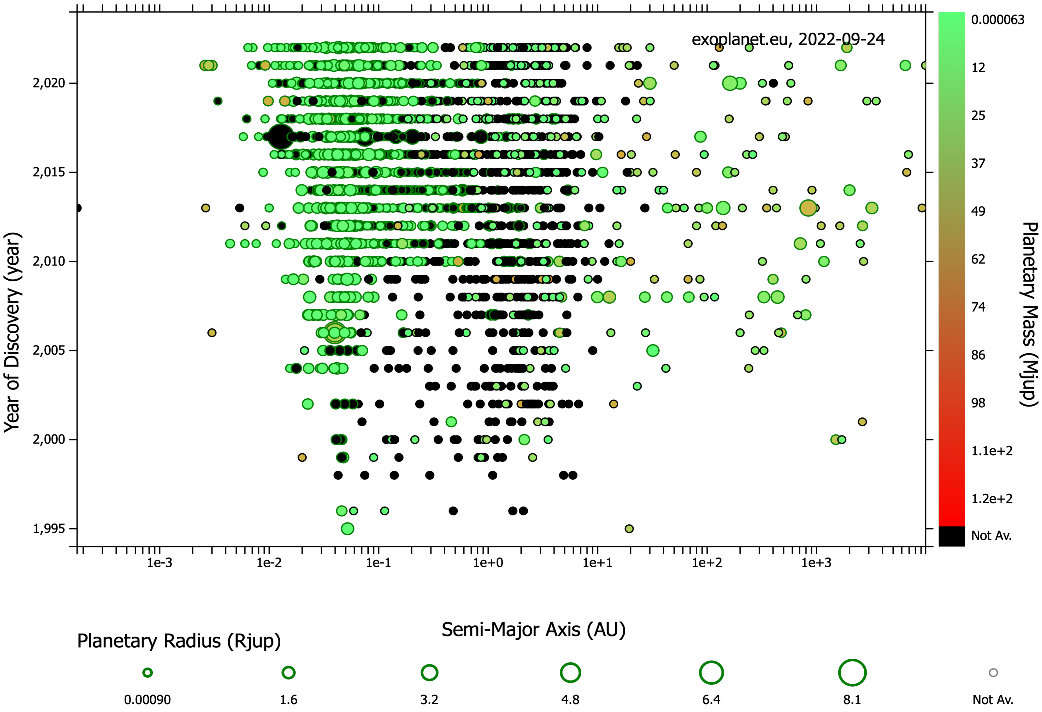

Figure 1.2: The sub-sample of about 3400 confirmed exoplanets is plotted in the year of discovery versus semi-major axis graph. Planets with measured and confirmed mass and radius are overplotted with a color scale. In addition, the radius of the planet is represented with a corresponding size of the green circle. The sample of planets with mass and radius is about 1400 planets. Graphs were prepared with tools provided by the portal exoplanet.eu of The Extrasolar Planets Encyclopaedia - web: http://exoplanet.eu

is illustrated in Fig 1.2 where all up to date (end of 2022) known planets with measured mass and radius are shown. The number of planets with both values measured was 1244 and the number of all planets in the catalogue is 5183 (number from http://exoplanet.eu). Therefore, we have only about 20 % of fully characterised exoplanets. This was the motivation for setting new strategies for space missions like *TESS* and *PLATO* which focus on brighter stars available for the ground-based characterisation. More details will be explained further in the thesis.

Nowadays, the instrumentation evolved from that installed on 2-m class telescopes in times of the first spectroscopic exoplanet surveys in the past century. Apart from the searches using the cross correlation method to obtain radial velocities and the first absorption cells to boost the radial velocity accuracy Griffin [1973], Campbell & Walker [1979], one of the first instruments which paved the way for high precision radial velocities was the CORAVEL (CORrelation-RAdial-VELocities) [Baranne et al., 1979] spectrograph, installed on 1-m Swiss telescope at the Observatoire de Haute Provence France in 1977 and another at the 1.54-m Danish telescope at the La Silla Observatory in Chile. CORAVEL spectrographs were able to achieve accuracies of 250 m/s which at that time was unprecedented. The development of new instruments continued and again on 2-m class telescopes with instruments such as the ELODIE [Baranne et al., 1996] and SOPHIE [Perruchot et al., 2011] spectrographs, both mounted at the 1.93-m telescope at Observatoire de Haute Provence, France. A similar survey searching for extrasolar planets was the Carnegie Planet Survey[5] [Butler & Marcy, 1996]. ELODIE was the échelle spectrograph which detected the 51 Peg b planet in 1995 and was replaced with SOPHIE for which an octagonal fiber was used to improve the accuracy of radial velocities. Next step was again made within the 2-m class telescope when CORALIE was installed in 1998 at the 1.2-m Swiss telescope at La Silla observatory, Chile [Marmier et al., 2013]. The accuracies of the radial velocity measurements were inching closer to 1 m/s [Queloz et al., 2001]. This process concluded with the HARPS spectrograph which is currently installed at ESO 3.6-m telescope at La Silla, Chile [Mayor et al., 2003].

HARPS demonstrated an unprecedented precision of the measurements even below 1 m/s. The HARPS spectrograph opened a new window into exoplanet detection and characterisation. However, HARPS is operated by the ESO, and thus obtaining telescope time is a highly competitive process. The next logical step was ESPRESSO (SPectrograph for Rocky Exoplanets and Stable Spectroscopic Observations) which started operations in 2019 from the Paranal observatory in Chile using the power of up to four 8.2-m telescopes. ESPRESO is an extremely precise instrument capable of measurements down to 25 cm/s and the plan is to reach 10 cm/s in radial velocity [Pepe et al., 2021]. This allows to characterise even small terrestrial planets. However, the second Earth as we know it from our solar system would require perhaps even better precision as the expected changes in radial velocities would be around 11 cm/s. Again, ESPRESSO is operated by ESO, and the telescope time access is awarded on highly competitive basis.

There are also other spectrographs on other observatories which are capable of high-precise measurements but we listed here a representative sample which was at the beginning of the exoplanet hunt race and some current state-of-the art instruments. It can be seen that the precise instrumentation was developed for the 2-m class telescopes initially and some improved and upgraded form, it is still present on those telescopes. There is an extremely high demand for the instrumentation which is capable of precise measurements from 1 m/s up to a few hundreds of m/s. The high demand is fed by the exoplanetary space missions such as *CoRoT*, *Kepler*, *TESS* and in the future *PLATO* which required, require and will require an extensive ground based follow-up to fulfil the mission goals.

This habilitation thesis describes the original research of the author in the last almost two decades in the field of exoplanets and it is presenting 7 scientific papers where the author was the first author or where he published with his students. We highlight the role of the ground-based telescopes supporting the exoplanetary space missions and then especially the instrumentations on mid-aperture telescopes for the detection and characterisation of exoplanets.

The author was active with survey telescopes helping to support the space mission *CoRoT* in the early years of the new millennium. Later, the author founded an exoplanet research group in the Czech Republic and started to contribute to precise measurements of radial velocities allowing characterisation of distant exoplanets: the focus was on the instrumentation for the 2-m class telescopes.

---

[5] http://exoplanets.org/science.html

Thus, in the first part, research achievements and development from the era of the *CoRoT* mission, where the author was part of the mission team, is described. The first steps to support the space mission from the ground with a photometric telescope are presented in scientific papers which are accompanied with an introduction into the topic. We present our contribution to a spectro-photometric follow-up in Section 2.1. Then, as an example of a 2-m class instrumentation dedicated for the ground-based follow-up, the restart of operations of the Ondrejov Échelle spectrograph (OES), Ondřejov, Czech Republic is presented. The OES operations were made efficient for the ground-based follow-up of brighter *Kepler* exoplanet candidates and almost all *TESS* exoplanetary candidates. Section 2.2 and Section 2.3 presents also an example of exoplanet detections achievable with 2-4-m class telescopes and interesting cases how the 2-4-m class telescope can contribute to statistical studies . Finally, in Section 2.4 we present also a new project PLATOSpec which will be used for the *PLATO* space mission ground-based support.

In the second chapter, the focus shifts towards the characterisation of exoplanets. We present an interesting science niche for 2-4-m class telescopes which is the transmission spectroscopy in Section 3.1 and characterisation of exoplanetary atmospheres, in particular of gas giants presented on a few examples 3.2. The content of the thesis is summarised in a brief Conclusions section.

1.1 The zoo of exoplanets

The first officially discovered exoplanet 51 Peg b is a gas giant planet with many similarities to our Jupiter, but on a very short orbit [Mayor & Queloz, 1995]. After the confirmation of 51 Peg b, our view on exoplanetary systems has changed forever. The classical theory of planetary formation was described e.g. by [Mordasini et al., 2010] or formation of our solar system in particular by [Pfalzner et al., 2015]. After the formation of a central star and a disc in a gravitational collapse, the planetesimals form. Small and large planets have slightly different formation mechanisms, described as the Nice model, [Gomes et al., 2005] and [Tsiganis et al., 2005], respectively. However, an important role in the formation of our solar system had migration of giant planets. There are some extensions of the Nice model such as Jumping-Jupiters scenario and Grand tack theory which describe how the migration of large planets could have happened and what consequences the migration of gas giants had for our solar system [Walsh et al., 2011]. Thus from our solar system we know that the process of building of a planetary system is relatively short taking only a few million years but it can be quite vigorous [Morbidelli et al., 2005, Nesvorný & Morbidelli, 2012]. TheGrand tack hypothesis offers many similarities of solar system formation with exoplanetary systems formation. But to describe the gas giants on very short orbits, we need to find a mechanism how they can be created because there is not enough material so close to the star to build a gas giant [Lin et al., 1996].

The first theories of exoplanet formation were proposing the role of migration process and its responsibility for the close-in orbits around the host stars, however, also the first possible in-situ formation models were presented [Bodenheimer et al., 2000]. However, later with the discovery of smaller planets, even an in-situ formation of gas giants was proposed. In the in-situ formation, smaller planets might have play a big role as core for future gas planets [Batygin et al., 2016, Boley et al., 2016, Hasegawa et al., 2019]. But we were asking the crucial question, where were all the small planets?

However, the first small planets began to emerge around 2005. There were two types of planets discovered. The first type, called Super-Earths, represented by e.g GJ876 b or even a multiplanetary system GJ581b with planetary masses up to 10 $\mathrm{M}_{\mathrm{Earth}}$ [Rivera et al., 2005, Udry et al., 2007]. The second group of planets contained bodies of a size of our Neptune and perhaps the first such planet was GJ436 b [Butler et al., 2004]. The first rocky Super-Earth planet around a G-type star was the planet CoRoT-7 b discovered by the *CoRoT* satellite shortly after its launch. The planet CoRoT-7 b is orbiting its star within only about 20 hours. The planet has a radius of about 1.5 Earth radii [Léger et al., 2009]. The CoRoT-7 b is an excellent example demonstrating the complexity of the validation process. The light curve of CoRoT-7 b was plagued by the stellar variability and the transit depth itself was in order of a few tens of parts per million (ppm).

The follow-up observing process was crucial and it is described in more detail here [Léger et al., 2009], providing a very nice insight into time and resources which are needed to confirm a small rocky exoplanet with an existing instrumentation. Everything changed later after 2009 with the *Kepler* mission as it started richly populating the branch of small planets - see Fig.1.3. We began to realise that smaller planets outnumber the large gas planets.

With growing number of different types of exoplanets we were able to make some first divisions between their types. The upper limit of 10 Earth masses for Super-Earths was proposed as a division line in one of the first studies describing the structure of Super-Earths [Valencia et al., 2007]. It is believed that Super-Earths might play a significant role in the in-situ formation of close-in gas giants [Batygin et al., 2016]. Moving to mini-Neptunes, an interesting example of that type of planets is GJ1214 b [Charbonneau et al., 2009]. The first analysis of the planetary environment hinted on the significant content of heavy elements in its atmosphere [Bean et al., 2010].

The measurements were showing an evidence that there might be a water vapour in the atmosphere of GJ1214 b. Therefore, the planet was labeled as a first so called ”water world”. We were also involved in the characterisation of the exoatmosphere of GJ1214 b [Bean et al., 2011, Cáceres et al., 2014]. In any case, the mini-Neptunes are very interesting group of planets, also because there seems to be a forbidden space for Neptunes on orbits shorter than 4 days. In that so called Neptune-desert, the planets perhaps can not retain their atmospheres, however, the exact reason is not yet understood Mazeh et al. [2016]. There is one exception though, NGTS-4 b which is located in the Neptunian desert and retains its atmosphere [West et al., 2019].

In terms of environment of exoplanets, we divide exoplanets in hot and warm. The division is given by the orbital period, planets of all known types orbiting in less than 10 days are called hot and above 10 days of orbital periods are warm planets. It can be seen, that nowadays, we are at point of very different landscape than in 1995, when we knew our solar system and a new type of gas giant on a short orbit.

Furthermore, as more and more exoplanets were discovered with more precise instrumentation, especially HARPS, astronomers were able to make first studies examining the statistical distribution of exoplanets [Wright et al., 2012, Dressing & Charbonneau, 2013, Kunimoto & Matthews, 2020]. It emerged, from the observed sample of stars, that the typical gas giant around a solar like star has an occurrence rate of about 1 % whereas the planet of the Super Earth mass has an occurrence rate of around 6 % [Wittenmyer et al., 2011, 2016]. However, a system like our own solar system has not been discovered just yet. We know that many planetary systems with small planets and also multiplanetary systems exist but we do not know, yet if any analogue of our solar system does exist. We also do not know whether an analogue to the Earth exists. However, at least the latter should change with the *PLATO* space mission which should provide an insight into ages of planetary systems and it should also discover several Earth analogues due to unprecedented photometric precision and mission design [Rauer et al., 2014]. The need for a precise ground-based follow-up observation, however, remains in place more than ever.

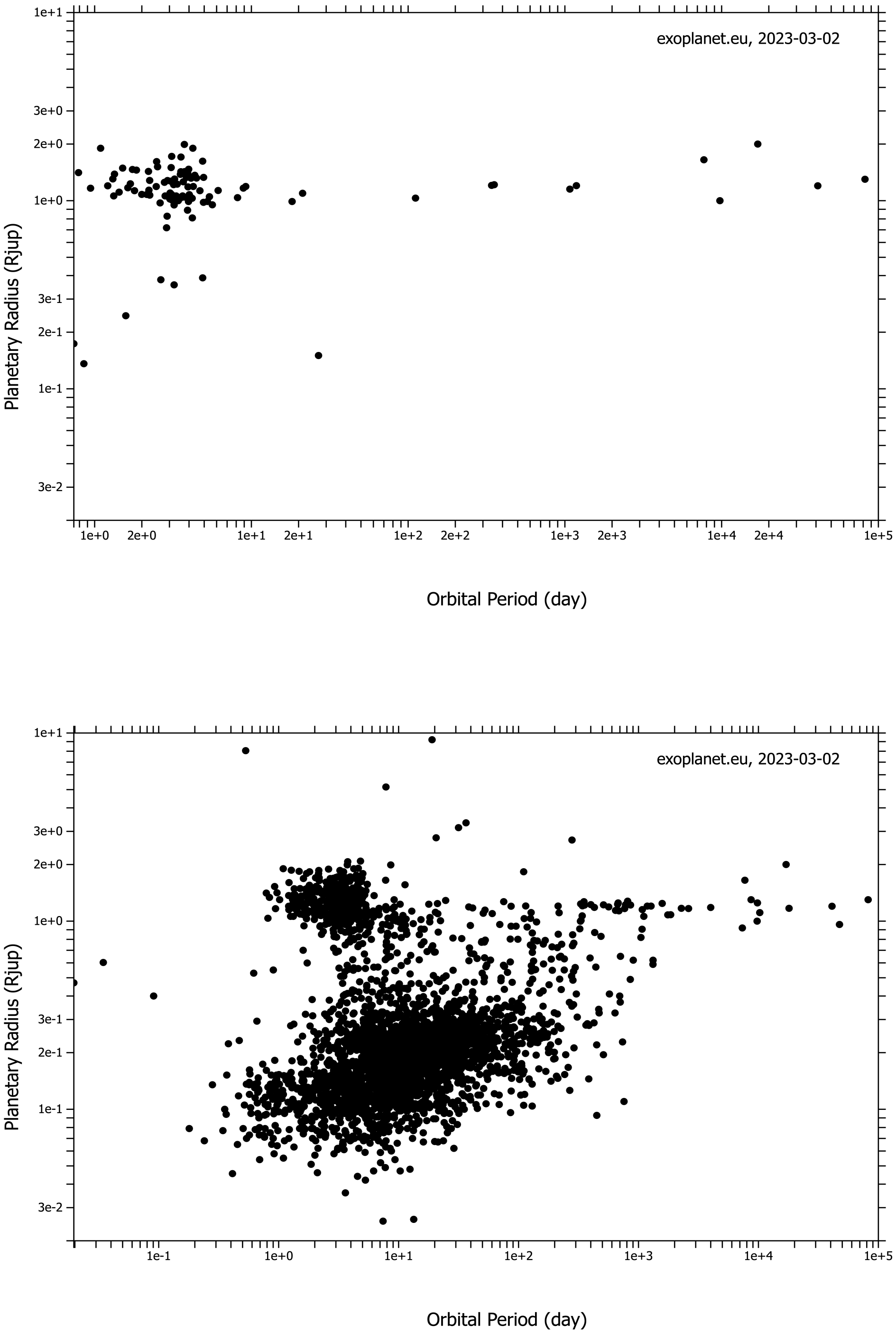

Figure 1.3: Top - Radius versus orbital period of known confirmed planet from 1995 until 2009, when *Kepler* was launched. Bottom - Radius vs. orbital period of known confirmed planets until 2018, when *Kepler* stopped operations. Graphs were prepared with tools provided by the portal exoplanet.eu of The Extrasolar Planets Encyclopaedia - web: http://exoplanet.eu

2. Ground-based instrumentation supporting space missions

The ground-based follow-up observations for space missions are very telescope time consuming as we discussed in the general introduction. Each of the steps needs to be very well coordinated and justified in order to not waste the telescope time. The difference in concepts in space missions *CoRoT*, *Kepler*, *TESS* and *PLATO* were discussed in the Introduction. But it is clear that selection of the core sample of stars influences directly the efficiency of the ground-based follow-up. The *TESS* and *PLATO* missions are designed so that the ground-based follow-up is the integral part of the missions.

The telescope time for each step depends on the brightness of the host star and on the expected size of the planetary candidate. The smaller the planet is the more difficult the characterisation is. A hot-Jupiter with a median brightness of $V = 10.5\,\mathrm{mag}$ typical for the *TESS* and with a semi-amplitude in radial velocities of 300 m/s, orbital period of a few days around a solar like star can be characterised within minimum of about 15 hours of observing with a typical 2-m telescope with a spectrograph such as OES described in our paper [Kabáth et al., 2020]. The two spectra will deliver the information about the stellar parameters and if taken in oposit phases, they can also hint on the amplitude or variability scale in general.

We illustrate the time requirements on a practical example. We usually need at minimum two exposures as the first screening. If we assume each exposure is 900 seconds, we need at least half an hour for the very first check on the host star and perhaps also on the semi-amplitude of the radial velocities. In the next step, even a large aperture telescope would need several radial velocity measurements, one exposure of 1800 seconds, each. That amount could easily add-up to several observing nights. The telescope time required for the HARPS instrument at La Silla would be perhaps the half of the smaller telescopes, however, it is awarded on highly competitive basis. However, as HARPS is one of the few instrument which has an accuracy in cm/s regime, lot of the telescope time is needed to characterise small rocky planets which require even more telescope time to reach required precision. Therefore, spreading the tasks among various telescopes based on the parameters of the planetary candidate proves efficient and allows for characterisation of larger group of targets. Furthermore, as HARPS is used for smaller planets characterisation, the gas giants might be a bit neglected due to lack of telescope time available. However, even precise radial velocities for gas giants and perhaps Neptune-sized planets are one of the foci for 2-4-m aperture telescopes.

2.1 Photometric follow-up

The whole process of the follow-up observing also includes the photometric observations. In the first step typically a small aperture telescope, equipped with a CCD detector such we had in our BEST and BEST II projects [Kabath et al., 2007, 2009], provides the first monitoring of candidates. Furthermore, imaging systems can resolve the contaminants in the aperture of the space mission, what can be a problem especially for the *TESS* mission. We selected one paper, published with, at that time, a student Thomas Fruth, to present here as an illustration of our contribution to the follow-up process. In the paper, [Fruth et al., 2012], we present an improved search algorithm used for the survey telescope BEST II. One of the first instruments dedicated solely to a ground-based photometric follow-up was above mentioned BEST II telescope, located at the Observatorio Cerro Murphy, Chile - next to Cerro Armazones, site of the ELT telescope - and operated remotely from Europe (see Fig. 2.1).

BEST II was a 25-cm Baker-Ritchy-Chrétien telescope equipped with a 4k×4k CCD which was observing the field-of-view (FoV) of about 1.5 deg on the sky [Kabath et al., 2009].The main purpose of the system was the photometric observing ahead of the *CoRoT* space mission launch. Typical FoV is presented in Fig. 2.1. It was possible to alternate between two different stellar fields, covering thus the full *CoRoT* exoplanet target field. We were able to prepare catalogs of variable stars and interesting objects [Rauer et al., 2010]. Another task which can be pursued with small telescopes with a photometric camera is regaining the ephemerides and also long term observing in case only one transit was detected by the space mission [Cooke et al., 2018]. We contributed to a candidate vetting process of the *CoRoT* space mission. Nowadays, a good example of ground-based photometric follow-up instrument is the project MUSCAT2, which is a 1.5-m robotic telescope located at Tenerife, Spain. MUSCAT is intended for the *TESS* and later *PLATO* space mission follow-up [Narita et al., 2019]. Another survey operating from the ground is the New Generation Survey Telescope (NGTS), located at European Southern Observatory at Cerro Paranal, Chile [Wheatley et al., 2018]. Interesting discoveries by the NGTS were planets in the mini-Neptune regime, one of them was NGTS-4 b a planet in the mini-Neptune desert described in the Introduction [West et al., 2019]. The systems listed here do not offer a complete overview on the projects currently available for the candidate vetting process, rather than an illustration how important is the photometric follow-up. Finally, small telescopes play another important role. As the small aperture telescope and an efficient CCD camera are relatively affordable, they are used with many citizen astronomers. A high quality photometry can be performed by the citizen astronomers who offer telescopes placed at various locations on the Earth surface and capable of measuring with the milimagnitude precision. Recently, an interesting initiative for long-term monitoring of selected *TESS* systems with small photometric telescopes was proposed [O'Conner Peluso et al., 2023].

Just for completeness, we have to mention the next step, a photometric imaging with high spatial resolution with large facilities with Adaptive Optics. We mention here only an example as this is relevant mostly for large aperture telescopes [Ziegler et al., 2017] and thus beyond the scope of this thesis. However, the photometric follow-up is an integral part of planetary candidates validation process and many papers describe the need for it [Pasternacki et al., 2011, Klagyivik et al., 2013, Fruth et al., 2013]. Clearly, an efficient candidate vetting process requires the synergy between ground-based spectroscopic and photometric facilities which nowadays include even citizen astronomers.

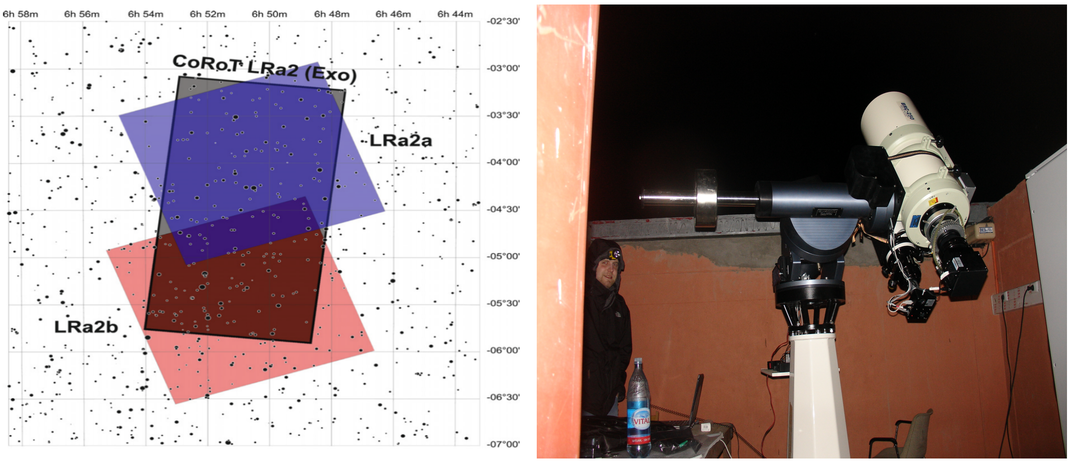

Figure 2.1: Left - The orientation of the exoplanetary *CoRoT* field and the BEST II target fields LRa02. Right - image of the BEST II telescope. Figures are from Kabath et al. [2009] and from the archive of Petr Kabáth.

2.2 Precise spectroscopic instrumentation for 2-m class telescopes

The role of mid-aperture telescopes is increasingly important for reasons discussed in the above paragraphs. Smaller telescopes with precise spectrographs are especially valuable. Here we will describe our contribution to follow-up efforts with 2-m class telescopes.

The Perek telescope was inaugurated in 1967 and it was used for many scientific programs. In 2018 a new exoplanetary research group was founded by the author of this thesis at the Astronomical Institute at Ondřejov, Czech Republic. At that time, the group was driven by the outlook of the *TESS* space mission which was planned to deliver several thousands of new planets. Therefore, a large amount of telescope time was foreseen to be needed in the near future.

The author's team initiated the verification of the instrument OES first described in Koubský et al. [2004] and tested its suitability for exoplanetary research. Recent OES description and its capabilities is described in Kabáth et al. [2020]. Simultaneously, we started to take scientific data with the OES spectrograph and fine-tuned the usage of the 2-m telescope for exoplanets follow-up. The typical follow-up of the candidates consists of various steps described below. For the most parts of the ground-based follow-up a lot of telescope time is required. Especially precise instruments on mid-aperture sized telescopes play an important role here. Paper Kabáth et al. [2020] presents our contribution to the following subtasks of the spectroscopic follow-up observing:

- Initial screening - this very first step of the follow-up observing should aim at obtaining a few high Signal-to-Noise Ratio (SNR), high-resolving power spectra of the host star. We can determine the parameters of the star by comparing the spectrum with stellar templates and models. In addition, we can determine the luminosity class of the star. The obtained parameters are crucial for the determination of the precise planetary parameters.

- Rejection of false positives - during this step, we can determine the nature of the system. Typically, we are looking for the value of the radial velocity semi-amplitude. Therefore, typically, the first check is to take spectra at two opposite phases. Typical semi-amplitude of a gas giant on short orbit is of the order of a few hundreds of m/s. This step is essential also for discriminating between promising and bad candidates. Therefore, even small rocky planets which are out of the reach of the mid-aperture telescopes can be observed and the outcome is the assessment of the quality of the candidate. Therefore, only very good candidates continue for larger facilities with very high-precision instruments.

- Precise radial velocities - the aim of this step of the follow-up observing is to obtain the orbital solution of the system. Usually, the candidates observed at this stage are the selected best systems with low probability of being false positives. The results of the observing are precise radial velocities measurement covering sufficiently the orbital phase of the newly detected planet. From the radial velocity curve and in combination with the transit observations a precise mass of the planet can be determined. The new planet is confirmed and fully characterised.

In the paper [Kabáth et al., 2020], the location of Ondrejov is described in terms of clear nights which are usable for a reasonable spectroscopic measurements. In Fig. 2.2, the typical amount of nights useful for observing is presented. It can be seen that Ondřejov is a typical central European location which can still offer up to 135 usable nights per year. This translates into about a maximum of 810 observing hours (assuming an average night of 8 hours) which is a significant amount of time when compared to the follow-up needs described earlier. Therefore, even observatories like Ondřejov can contribute to important science. The Perek telescope is equipped with OES, an échelle spectrograph, offering a resolving power of R=$50,000$. The wavelength range of OES spans from about 375 nm till 920 nm. The spectrograph is equipped with the 2048×2048 CCD chip cooled by the liquid nitrogen. The spectrograph is also equipped with an Iodine cell.

We performed verification tests in 2017-2018 to asses the stability of the radial velocities measurements. Our test campaign on standard stars spanning from one night to a year delivers the longterm stability in radial velocities of about 400 m/s (year) and down to 83 m/s for an intra-night stability. The monitored star HD109358 was $V = 5\,\mathrm{mag}$ bright. Furthermore, a result of the work was also a basic exposure time calculator graph showing the expected SNR versus brightness. The results with stability measurements are presented in Fig.2.2. However, it is to be noted that in 2020 a fiber upgrade was performed, thereby increasing the throughput. An implementation of data routines capable of reducing the data with the iodine cell were presented by Michaela Vítková in her master thesis [Vítková, 2020].

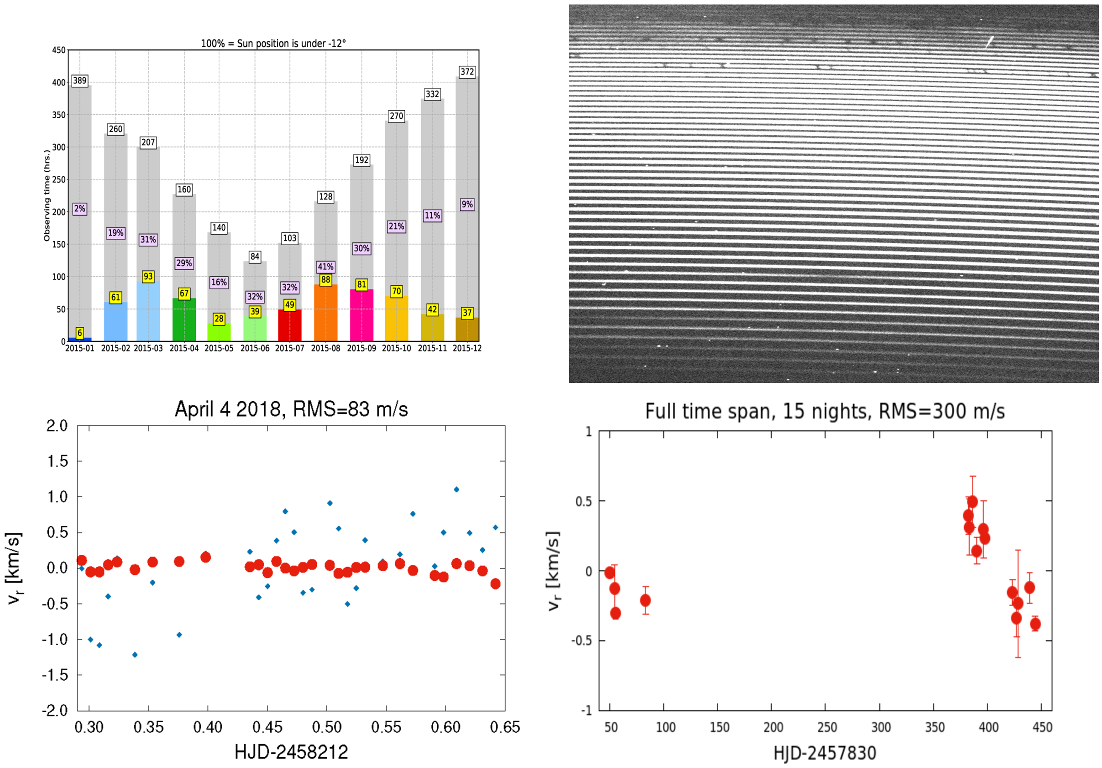

Figure 2.2: Top left) Histogram presenting the typical observing year with the OES instrument at Perek telescope. Colored columns mark the time with an open shutter and grey column mark the time in hours when the shutter was closed due to various reasons during the night time (Sun at -12 deg) - weather, technical, etc. (top left). On the top right panel an, échellogram from the OES spectrograph is shown. Bottom left and bottom right figures present the radial velocity stability of a radial velocity standard star HD 109358 measured over a night and several months, respectively.

2.3 Importance of ground based follow-up for the determination of the planetary distributions

The 2-m class aperture telescopes with instrument such as OES are powerful tools for the candidate vetting process. However, they can help also with deriving of distributions of large planets. We present here an example of a sample of *Kepler* A spectral type stars for which planetary candidates were claimed by [Balona, 2014]. His paper reported about 166 new giant planetary candidates in the *Kepler* field, however, all the candidates were derived from the photometric data only. The occurrence rate of giant planets is estimated to be roughly about 1 % [Wright et al., 2012]. For intermediate mass stars the theories predict even lower occurrence rate of gas planets of 0.15 %. But if our candidates sample were confirmed the occurrence rate would increase dramatically. Therefore, we used OES and the Tautenburg échelle spectrograph for validation of reported candidates. We obtained hundreds of radial velocity measurements for a dozen of stars

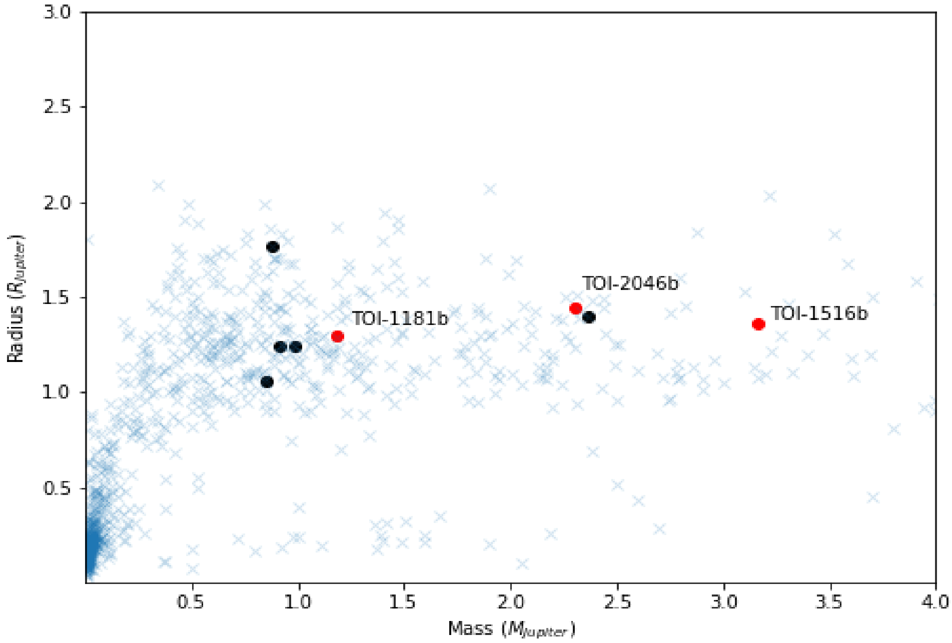

Figure 2.3: Three new gas giants, TOI-1181b, TOI-1516b and TOI-2046b, detected with 2-m class telescopes plotted with other known exoplanets. Figure is from Kabáth et al. [2022].

from Balona [2014] from the sample. However, our survey, which took place over 2 years, did not confirm any of the planetary candidates. Thus we determined the upper limit for the occurrence rates for gas giants around A (intermediate mass) stars as 0.75 %, in line with the lower end of occurrence rate expectation. Our work once again demonstrated the importance of smaller telescopes with precise instrumentation for contributing to important open questions of astrophysics such as determination of planetary distributions.

Our last paper presented here, Kabáth et al. [2022], reports on the characterisation of three new gas giants with help of the OES data. This is an example of typical use of 2-m class telescopes in the exoplanetary science. In this paper, we introduce three new planets TOI-1181 b, TOI-1516 b and TOI-2046 b on short orbits around F-type stars. The brightness of host stars is ranging from $V = 10\,\mathrm{mag}$ to $V = 12\,\mathrm{mag}$ and the transit depth is measured between 1-2 %. We were collecting the spectroscopic data from early 2020 till mid 2021 for all three candidates with OES.

Later, once the candidates were flagged as priority one candidates, we started coordination within the KESPRINT [1] consortium which is dedicated to ground-based follow-up of space based missions. The KESPRINT has access to an extensive range of ground-based facilities which can contribute to photometric and spectroscopic follow-up of candidates in a very efficient way. We used stellar spectra obtain with OES, Tull [Tull et al., 1995], TCES [Hatzes et al., 2003a] and

---

[1] https://kesprint.science

TRES [2] instruments to determine the spectral parameters of the host stars. Our three new planets are presented in Fig. 2.3 where the mass-radius diagram is shown. The reported planets populate the branch of gas giants and they demonstrate three interesting examples among large planets. Hot Jupiter TOI-1181b is an example of highly insolated planet by its host subgiant star, TOI-1516 b is a typical hot Jupiter system with a fe Gyr age and a TOI-2046 b is a very young and inflated planet. The evolutionary stages of the systems TOI-1181 and TOI-2046 are illustrated in Fig. 2.4.

The system TOI-1181 b is a very interesting system for further follow-up observations, even from the ground. Such system with high insolation might be observed to measure the albedo in the optical wavelengths additionally to the *TESS* light curves. The young inflated system TOI-2046 b is a good target to investigate further the orbital alignment via R-M effect which could reach as much as 80 m/s. We are only at the beginning of understanding of young systems, as systems with ages below 400 Myrs were counted only in single- and recently a low double-digit numbers. The interesting case would be also understanding of the mechanism which inflates the planetary atmosphere. However, presented gas giants from the *TESS* mission are only an example of science which can be performed with 2-4-m class telescopes with precise instrumentation. Furthermore, these systems offer the follow-up opportunities even with ground-based instruments at 2-4-m class telescopes.

---

[2] http://tdc-www.harvard.edu/instruments/tres/TRESdesign.pdf

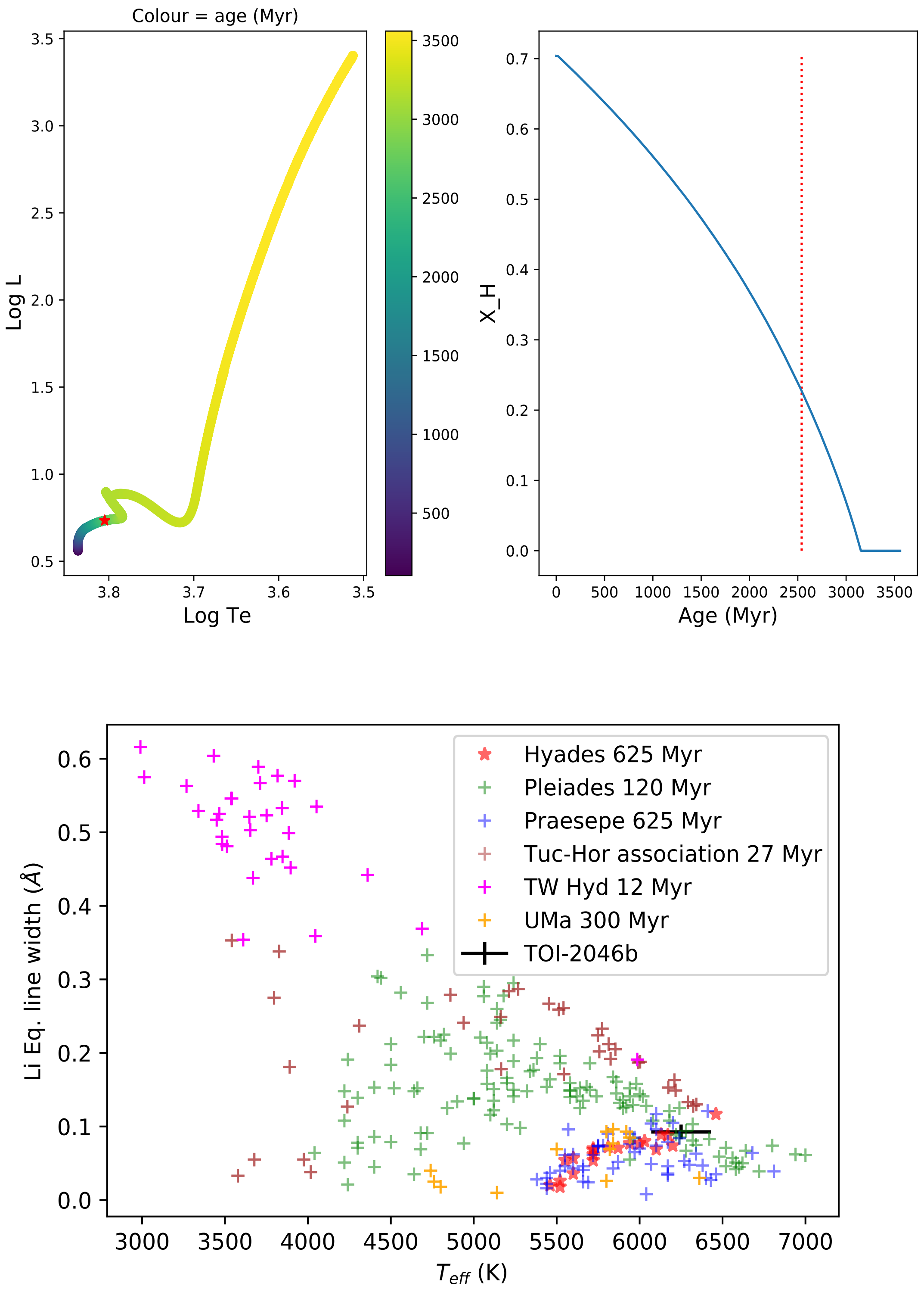

Figure 2.4: Top- Hertzsprung-Russel diagram for the system TOI-1181 where it can be seen that the host star left the main sequence recently and also the expected hydrogen content at the current age (red dotted line). Bottom - the age of the system TOI-204 was derived from the comparison of the lithium content with young open clusters, Figure is from Kabáth et al. [2022].

2.4 The PLATOSpec project - future ground-based follow-up facility

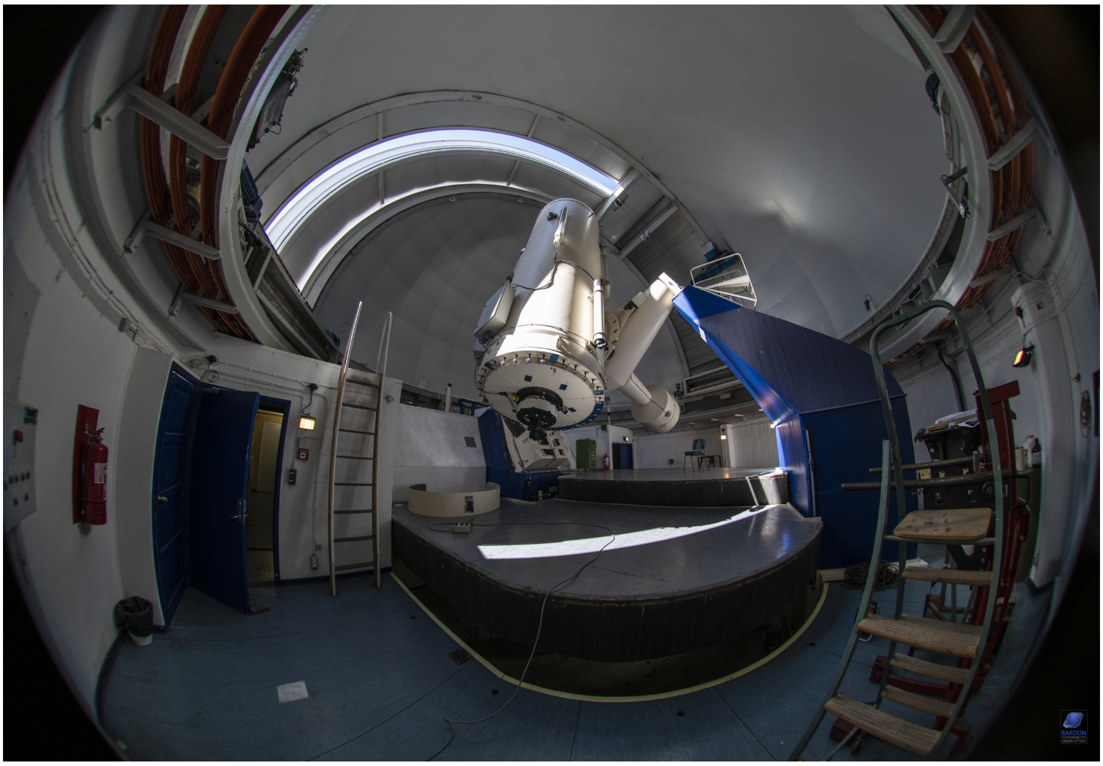

Figure 2.5: The E152 telescope. Image by Z. Bardon.

Our efforts to organise the future networks of telescopes with mid-apertures (2-4 meters) is demonstrated with a new project PLATOSpec. PLATOSpec will be a new spectrograph which will be operating from ESO, La Silla observatory, Chile[3]. The project is led by the Astronomical Institute of the Czech Academy of Sciences and the author of this thesis is the PI of the project. The consortium consists of colleagues from Thuringer Landessternwarte Tautenburg, Germany and Pontifica Universidad Catolica de Chile. The PLATOSpec spectrograph will be a high resolution échelle spectrograph with a resolving power $R = 70,000$ and wavelength range of 360-680 nm. The spectrograph will be mounted on a former ESO E152 telescope which operates now after a control system upgrade to allow the remote observing mode. The E152 telescope is depicted in Fig.2.5.

PLATOSpec will be a classical white pupil spectrograph which should aim for 3-5 m/s accuracy in radial velocities for the targets up to $V = 12\,\mathrm{mag}$. The scheme of the instrument is shown in Fig.2.4. The spectrograph will be equipped with a blue sensitive CCD which should offer an enhanced wavelength range for monitoring of the stellar variability in Ca H and K lines. The instrument will be fiber fed with an octagonal fiber into which light from the telescope front end will be injected through a system of microlense triplet. The front end will consist

---

[3] https://stelweb.asu.cas.cz/plato/index.html

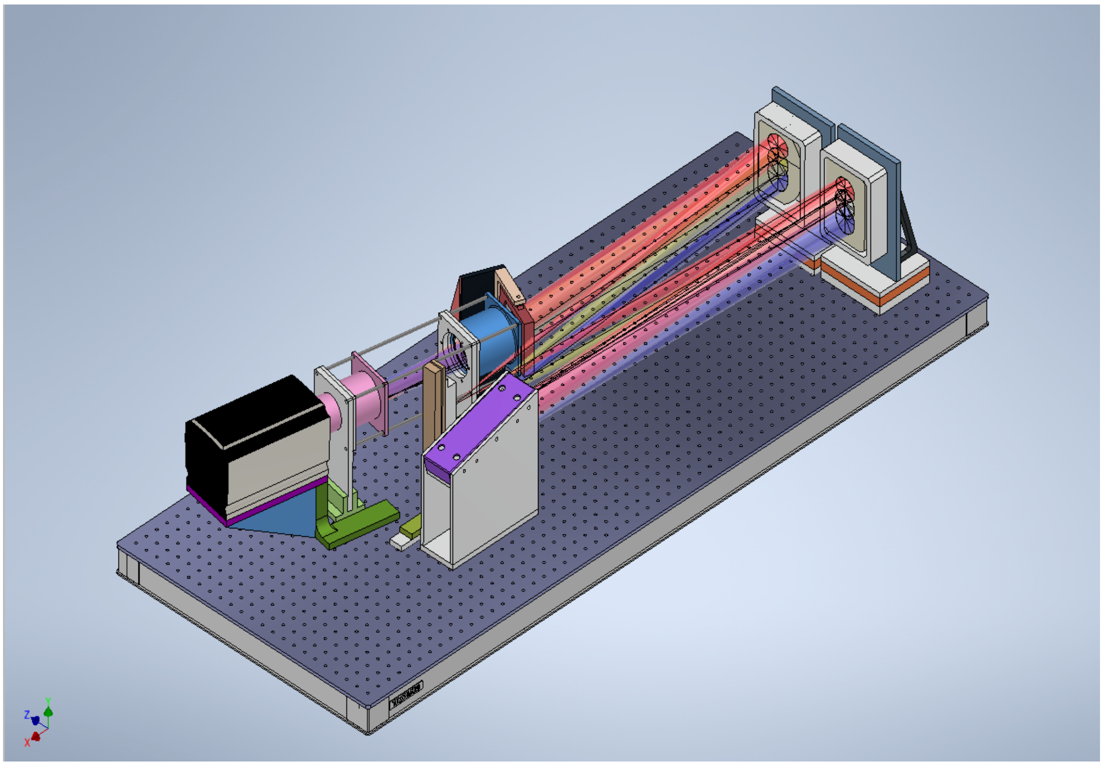

Figure 2.6: A drawing of the PLATOspec instrument. Image courtesy of L. Vanzi - The PLATOSpec consortium.

.

of autoguiding CCD and the fiber can be exchanged for a calibration fiber going to flat field and Thorium-Argon reference lamp. There will be also an iodine cell located in the front end. The spectrograph should arrive at La Silla in early 2024 and it should be operational after a brief commissioning period in the first quarter of 2024.

2.4.1 An interim spectrograph PUCHEROS+

The telescope E152 was upgraded with new control system in April 2022. In June 2022, a photometric CMOS detector was installed and we acquired the first test data of a few variable stars. In September 2022, an interim spectrograph PUCHEROS+ was mounted and we started the test observing. However, we need to make some adjustments of the dome and re-alluminize the mirror and the full operations is expected to begin in May 2023. PUCHEROS+ is a simple fiber fed échelle spectrograph with resolving power $R = 20,000$ and wavelength range of 390-730 nm (see [Vanzi et al., 2012]). The scheme of PUCHEROS+ is shown in Fig.2.7. The first light spectrum of a star of $V = 12\,\mathrm{mag}$ with a 1800 sec exposure time delivers the SNR of about 20-30 (around H_{alpha} spectral line), a good performance, especially, taking into account that the main mirror was not recoated since more than 20 years. Similar exposure with the OES instrument would have SNR of about 12. This spectrograph will be replaced by the PLATOSpec spectrograph in 2024.

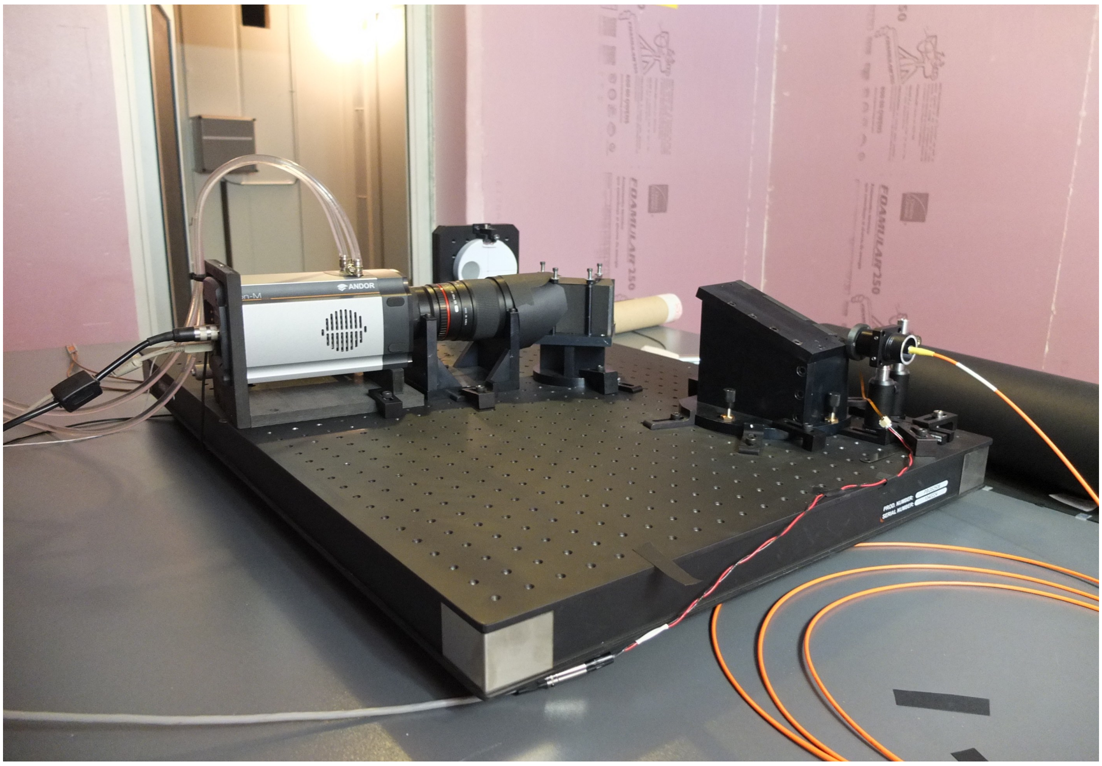

Figure 2.7: Photo of PUCHEROS+ spectrograph in the E152 spectrograph room. Image, courtesy of Leonardo Vanzi - The PLATOSpec consortium.

3. Exoatmospheres with 2-4-m class telescopes

Gas planets were the first planets discovered from the ground. The reason for the early discovery was perhaps the observational bias. In the Fig. 3.1, planets are ordered by their size and the year of discovery. It can be seen that with years and developing instrumentation, especially, the size of detected planets decreased. Of course, this is also an effect of *Kepler* which started to discover smaller planets. But it was much easier to detect a giant gas planet with the instrumentation in 1995 than the Earth-sized planet. The typical radial velocity amplitudes due to a giant planet are in orders of a few hundreds of m/s whereas a second Earth would introduce a radial velocity changes in orders of about 10 cm/s. Recently, giant planets offer an excellent science case for the 2-4-m telescopes.

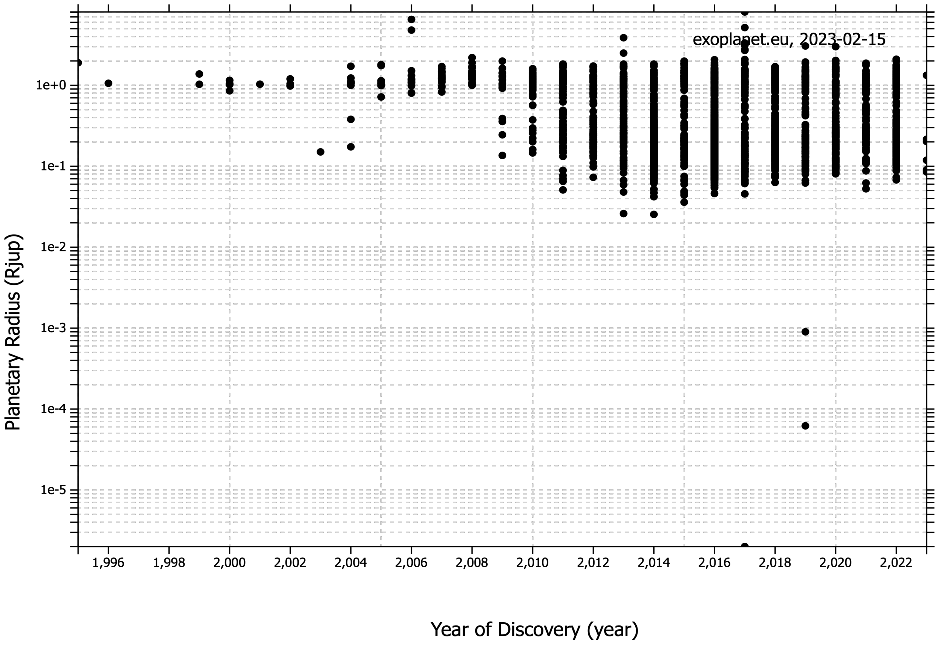

Figure 3.1: Exoplanets sorted by their radius and the year of detection. The graph was created with help of The Extrasolar Planets Encyclopaedia - web: http://exoplanet.eu.

Giant planets play their role in the evolution of the planetary systems. Gas giants might were most likely extremely important also for our own solar system and its development as we discussed in Section 1.1. The migration of Jupiter and Saturn influenced the orbit of the Venus and thus perhaps leaving it inhabitable [Kane et al., 2020] and as discussed in the introductory part the evolution of solar system might have been more similar to evolution of the exoplanetary systems than one would think. However, we are still at brink of discovering of more gas giants on long orbits as only a few systems were discovered so far and the dominant discovery method was direct imaging [Marois et al., 2008, Lagrange et al., 2009, Keppler et al., 2018, Macintosh et al., 2015]. The reason for a small number of known gas giants on long orbits is perhaps the need for a long-term monitoring and a need for relatively long-term high stability of the spectroscopic measurements. In order to detect our Jupiter, we would need to observe it for at least 10 years and we would need to reach a stability of about a few m/s over nearly 10 years to have a significant detection. The radial velocity signal induced by Jupiter is about 10 m/s. This combined with *PLATO*s ability of detection of analogues of solar systems opens a niche for smaller telescopes with proprietary telescope time which can monitor selected systems for a long time and which can offer a desired precision in radial velocities.

Gas giants are also the first exoplanets ever to be proven for their atmospheres. Before the launch of the first exoplanetary space mission *CoRoT* and later *Kepler*, the efforts were mostly concentrated on detection of new exoplanets to understand their statistical distribution. However, as many different exoplanets appeared, the race towards the understanding of the exoplanetary atmospheres and towards describing the exoplanetary environments in general began. The knowledge about the structure and composition of exoatmospheres can also help to understand the formation and evolution processes of exoplanets.

The most successful method to characterise exoatmospheres so far is the transmission spectroscopy. The series of spectra is taken before, during and after the transit of an exoplanet and by comparing of in- and out-of-transit spectra, the planetary atmospheric signature is detected in the residuals as an excess of the signal. The first detections of the atmospheres of exoplanets with help of this method were reported by [Charbonneau et al., 2002] from space. The first ground-based detections were reported by [Redfield et al., 2008, Snellen et al., 2008] mostly with large telescopes. However, as more suitable planets in terms of brightness and atmospheric imprint strength were discovered, also smaller telescopes started to play a significant role [Wyttenbach et al., 2015]. Typical elements detected in the exoatmosphere of a giant planet is sodium, potassium but also hydrogen and lithium [Chen et al., 2018, Keles et al., 2019] as these are usually the most abundant and relatively easy to detect than other elements such as water or TiO. Furthermore, the close-in hot planets with extended atmospheres containing hydrogen usually indicate evaporating atmospheres, like in an exemplary case of KELT-9 b [García Muñoz & Schneider, 2019].

3.1 Gas giants, case for 2-m telescopes

We present another example, to demonstrate the suitability of 2-4-m class telescopes for the characterisation of exoplanetary atmospheres. We used the 2.2-m MPG telescope at La Silla with the FEROS spectrograph [Kaufer et al., 1999] to obtain a transmission spectroscopy of a hot gas giant Wasp-18 b. We used the system Wasp-18 b as a benchmark and a scaling system for estimate of detection thresholds for 2-m class telescopes. Some basic formulas which describe the sodium signal expected from the exoplanetary atmosphere are as follows:

$$\Delta\delta \simeq \frac{2nHR_p}{R_s^2} \tag{3.1}$$

with R_s the stellar radius and n is the number of atmospheric scale heights (H) given by

$$H = \frac{k_B T_p}{\mu_m g}, \tag{3.2}$$

where k_B is the Boltzmann constant, T_p is the temperature of the planetary atmosphere, μ_m is the atmospheric mean molecular weight and g is the planet surface gravity, $g = \kappa \times M_p/R_p^2$, with M_p and R_p being the mass and radius of the planet respectively. We use the above formulas to determine the signal $\Delta\delta$ of exoatmosphere in the transmission spectrum. Furthermore, it can be seen that hot atmospheres with high hydrogen content are usually extended with high scale heights H. On the other hand, Earth-like atmospheres containing heavy elements are enclosing the planet tightly. In our example, for sodium, we assumed $\mu_m = 2.2$, and $n = 6$ which is typical for high altitudes as sodium is typically detected at high levels. Our choice is limiting the group of targets to planets with large abundances of sodium but these are perhaps the most suitable targets for 2-m class telescopes. When no measured value of T_p were known, we used the equilibrium temperature with all its limitations. We reproduce here an important figure 3.2 from our paper which shows the residuals of the data and then injected signal [Kabáth et al., 2019].

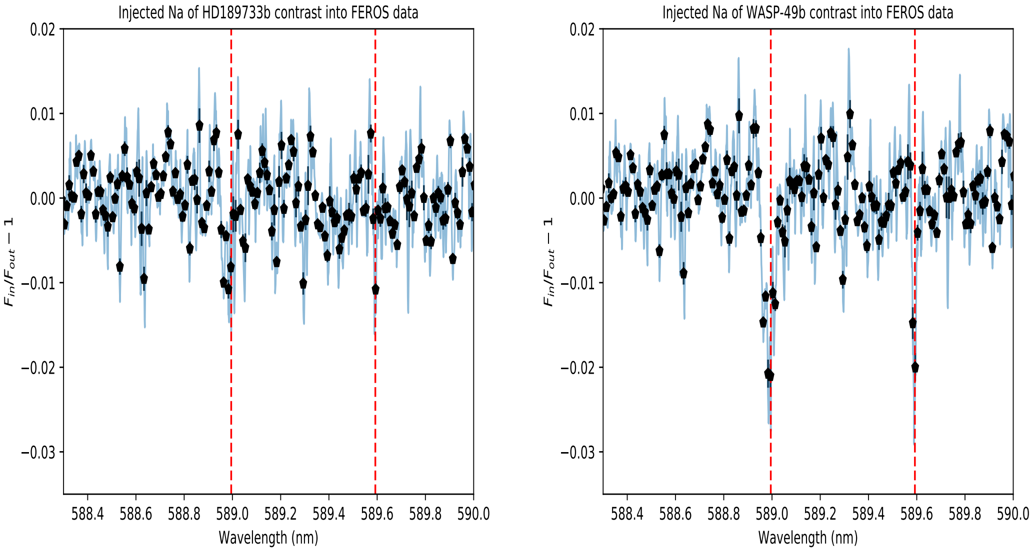

Figure 3.2: Signal of sodium injected in the Wasp-18 b data with parameters of expected signal of HD189739b (left) and the same but with parameters of expected signal of Wasp-49 b (right). Dotted line marks the position of the sodium doublet on the wavelength axis. Figure from [Kabáth et al., 2019].

As a reference for the sodium abundance we took HD189733 b [Wyttenbach et al., 2015] and of Wasp-49 b [Wyttenbach et al., 2017]. HD189739 b was one of the first planets for which a sodium in the atmosphere was reported by means of transmission spectroscopy, whereas Wasp-49 b is one of the hotter planets with an exoatmosphere. Our experiment provides a detection threshold for 2-4-m class telescopes shown in Fig. 3.3 from our paper [Kabáth et al., 2019].

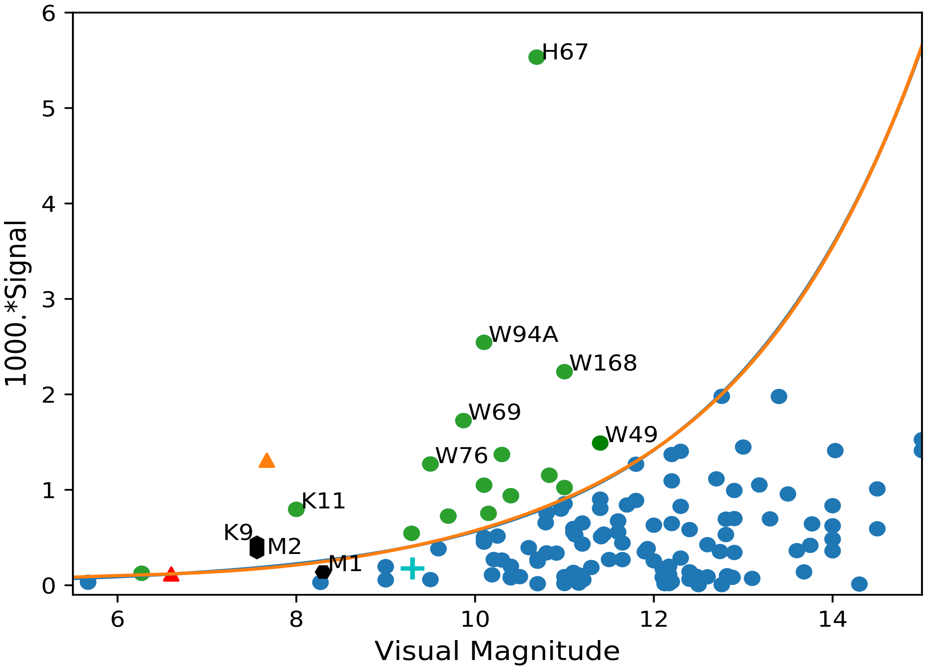

Figure 3.3: The figure shows suitable candidates for follow-up with 2-m class telescopes sorted by magnitude if they would have sodium abundant as HD189739 b which is in this case our reference (orange triangle). The orange line is the limit for the 2-m class telescopes, red triangle is rescaled HD189739 b signal for 2-m telescopes and light blue cross corresponds to Wasp-18 b signal itself. Figure from [Kabáth et al., 2019]

3.2 Combining spectroscopy and photometry

As the combination of spectroscopic and photometric data is essential for the ground-based follow-up, it can prove useful also for the obtaining of a transmission spectrum of an exoatmosphere. We present here a paper prepared by, at that time student, Claudio Caceres Cáceres et al. [2014] describing a project which the author of the thesis was leading and preparing. The min-Neptune GJ124 b described as a prototype of mini-Neptunes has suitable parameters for detection of its atmosphere. The host star is an M dwarf star and thus the transit depth is relatively large [Charbonneau et al., 2009]. The first characterisation of exoatmosphere of GJ1214 b was reported by Bean et al. [2011] and Bean et al. [2011], in the latter the author was a team member responsible for obtaining of the high quality data. However, the idea is to observe the transit of the exoplanet spectroscopically with a low resolution spectrograph capable of observing multiple stars. Each spectra in the time series is then divided into defined wavelength bands and the flux in each wavelength band is integrated to obtain the spectrophotometric light curve. Multiple stars observed simultaneously are used as comparison stars to correct for various effects, such as atmospheric extinction and instrumental effects. Here we present our contribution of spectrophotoetric data taken with the SOFI instrument at ESO NTT telescope in Chile with H+K grism. A set of photometric near infrared measurements taken with a narrow band filter centered at 2.14 μm filter with SOAR telescope and its OSIRIS instrument. Further transit was observed also with SOAR telescope but with SOI instrument in an I (Bessel) filter. The optical and near-infrared data were taken during different transit events and from the spectra a spectrophotometric flux was produced and the target flux was compared with he comparison star flux available in the FoV of the SOFI. The resulting transmission spectra from the combined data sets is presented in Fig. 3.4. We were able to exclude the hydrogen rich exoatmosphere scenario as we could not confirm the previously reported measurements by Croll et al. [2011] claiming a hydrogen rich atmosphere.

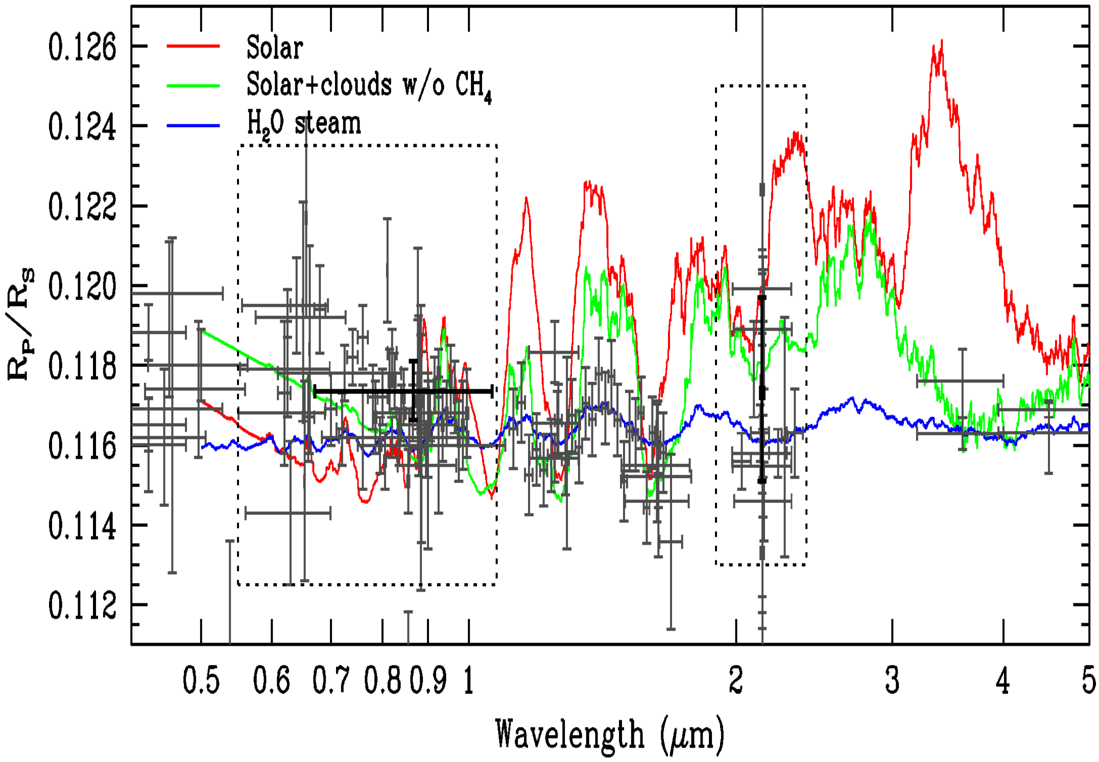

Figure 3.4: The figure presents a transmission spectrum with various models and with the measurements of the authors team marked in bold black symbols.. The near-infrared point obtained by our team does not suggest a hydrogen atmosphere of GJ1214 b Figure from [Cáceres et al., 2014]

We present here one more interesting example of a multiband measurement during the transit to obtain a transmission spectrum. The OSIRIS instrument at the Gran Telescopio de Canarias, Spain, offers so called tunable filters [1]. The tunable filters allow to set the desired wavelengths and thus obtain multiple band light curves as was presented by Sing et al. [2011] who reported detection of atmospheres for various planets. An important contribution towards characterisation of the content of exoatmospheres was presented by Nascimbeni et al. [2013] who measured the slope of the transmission spectrum in the blue wavelength region. The multi band measurements obtained for the mini-Neptune GJ3470 b corresponded to a Rayileigh scattering model which would indicate the existence of the small dust particles in the exoatmosphere. The low resolution spectroscopy or spectrophotometry and multiband photometry are offering an interesting complementary tool to high resolution transmission spectroscopy.

3.3 Sodium in the transmission spectra of hot Jupiters

As was reported by [Wyttenbach et al., 2015] HARPS is an ideal instrument (from 2-4-m class telescopes instrumentation) for the detection of exoatmospheres with transmission spectroscopy. In case of HARPS, another advantage is that many data sets were taken to obtain the Rossiter-McLaughlin (R-M) effect during the transits. R-M effect offers a description of the planetary orbit [Triaud, 2018]. Therefore, an additional analysis of such data sets to detect the atmospheric signature can be of a very high scientific gain. As an example, we present here the data set of four gas giants among which was the planet Wasp-76 b obtained with HARPS in 2017 within ESO Program IDs:090.C-0540(F), 098.C-0304(A). We performed the analysis as described above in the presented paper [Žák et al., 2019] where for Wasp-127 b we were able to confirm previous detection with other methods [Palle et al., 2017] and for Wasp-76 b, we confirmed simultaneously with other team [Seidel et al., 2019] a signature of sodium in the planetary atmosphere. The typical signature of sodium which we detected is shown in Fig. 3.5.

Characterisation of exoatmospheres of gas giants such as the one for Wasp-76 b lead usually to further interesting results [Kawauchi et al., 2022, Landman et al., 2021, von Essen et al., 2020, Kawauchi et al., 2022, Tabernero et al., 2021]. Furthermore, the process serves also as a benchmark and test laboratory for improving of observing methods such as the impact of the telluric lines removal and a refinement of the method [Seidel et al., 2020].

Obviously, the detection of exoatmospheres can not be a main scientific focus of the 2-m telescopes. However, the characterisation of exoplanetary atmospheres can be an interesting filler program for 2-m class telescopes. Furthermore, such medium-sized telescopes and their instrumentation usually come with a lot of proprietary time as they are working as so called hosted projects, e.g., at La Silla, Chile (E152[2], FEROS[3], TRAPPIST[4]). This aspect of telescope time is crucial, as the transit and thus the time series can be obtained during multiple transits. Exoatmospheres might be an interesting niche for 2-m class telescopes.

---

[1] http://www.gtc.iac.es/instruments/osiris/

[2] https://stelweb.asu.cas.cz/plato/

[3] https://www.eso.org/sci/facilities/lasilla/telescopes/national/2p2.html

[4] https://www.eso.org/public/teles-instr/lasilla/trappist/

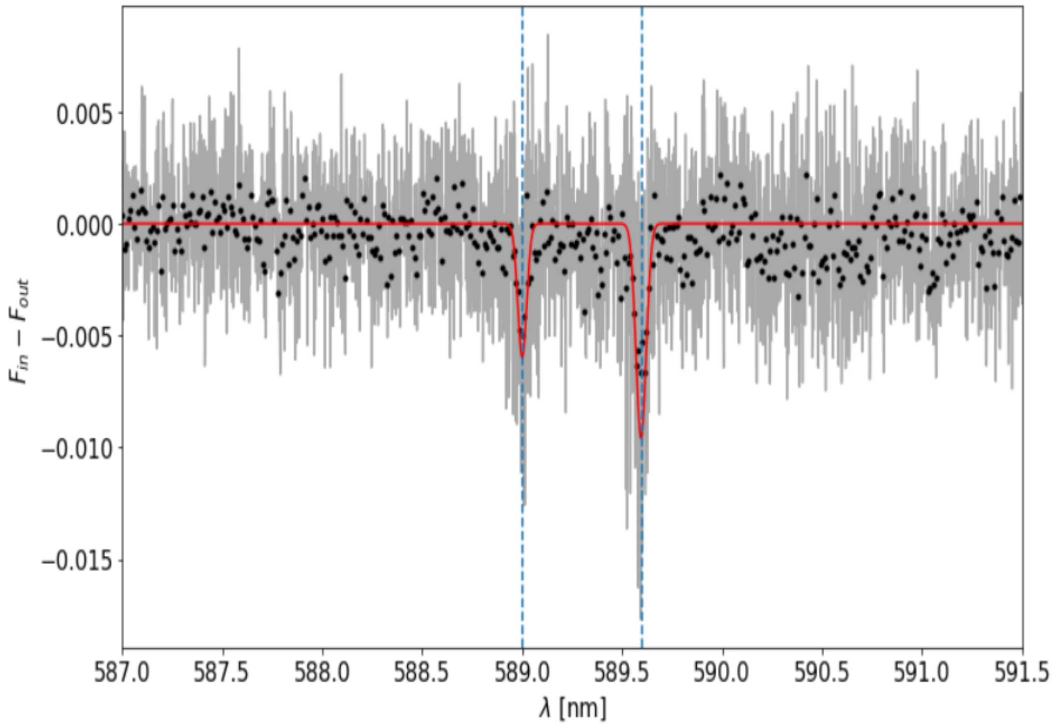

Figure 3.5: Signal of sodium in the exoatmosphere of Wasp-76b detected in HARPS archival data. Figure from [Žák et al., 2019]

Conclusions

Ground-based follow-up observing is an extremely important aspect of every exoplanet detection process. The early space mission such as *CoRoT* and *Kepler* clearly demonstrated that the planet confirmation is nearly impossible without follow-up observing. A newly detected planetary systems need to be characterised by measuring their radii and masses. However, measurement of mass and radius requires a combination of spectroscopic and photometric methods.Therefore, the process of validation of an exoplanetary candidate is very time consuming, as between the candidate discovery and its verification can be a delay of half a year or longer. A ground-based follow-up for exoplanetary space missions can be performed with a 2-4-m class of telescopes with precise instrumentation. Such telescopes usually have plentiful of telescope time available and they can deliver highly valued scientific results even in not optimal observing conditions, These projects complement the large facilities such as ESO and other large telescopes. We show here the importance of 2-4-m class telescope and propose also a few niche programs for them. The presented work from original papers published over the past 14 years present the changes of the field and increasing efficiency of planet validation and characterisation when 2-4-m class telescopes are used in an optimal way. We also presented an interesting but challenging science case for 2-4-m class telescopes which is the transmission spectroscopy to detect the exoatmospheres. Medium-sized aperture telescopes can not compete in efficiency in a single run with largest telescopes and its instrumentation. However, the valuable commodity for smaller telescopes is the telescope time.

In this thesis, we also showed the development and importance of the ground-based segment for the exoplanet characterisation process. We focussed mainly on smaller telescopes, especially 2-4-m class. In the first chapter, we described the ground-based follow-up with photometric method for the space mission *CoRoT* and in the remaining chapters, we showed the process of a spectroscopic follow-up for *TESS* and later a new concept for the *PLATO* space missions. We also discuss a special niche for the 2-4-m class telescopes which might be characterisation of exoatmospheres for gas planets. We conclude this work with the future outlook for the *PLATO* mission follow-up and we briefly introduce a new project PLATOSpec for which the author of the thesis is the PI.

The segment of 2-4-m class telescopes plays a crucial role for the validation and characterisation of new planetary candidates especially from space missions. Future development of instruments for these mid-aperture telescopes is crucial. Such instruments will be contributing to the efficiency of the planetary characterisation process when combined with large facilities. Smaller telescopes described in this thesis are typically operated by consortia of various institutes and they own the telescope time. Therefore, such systems, offer a unique observatory for time consuming, short and long-term monitoring projects and surveys. These telescopes are vital for the exoplanetary space missions for which they serve as a ground-based support. Furthermore, if these telescopes are used in networks, they can cover a long periodic planetary systems and they can offer even a better reliability. Therefore, we show that it is important to maintain and develop new instrumentations and to find their niche for a big science.

Bibliography

Alonso R., et al., 2004, The Astrophysical Journal, 613, L153

Auvergne M., et al., 2009, A&A, 506, 411

Balona L. A., 2014, MNRAS, 441, 3543

Baranne A., Mayor M., Poncet J. L., 1979, Vistas in Astronomy, 23, 279

Baranne A., et al., 1996, A&AS, 119, 373

Bashi D., Zucker S., Adibekyan V., Santos N. C., Tal-Or L., Trifonov T., Mazeh T., 2020, A&A, 643, A106

Batygin K., Bodenheimer P. H., Laughlin G. P., 2016, ApJ, 829, 114

Bayliss D. D. R., Sackett P. D., 2011, ApJ, 743, 103

Bean J. L., Miller-Ricci Kempton E., Homeier D., 2010, Nature, 468, 669

Bean J. L., et al., 2011, ApJ, 743, 92

Bodenheimer P., Hubickyj O., Lissauer J. J., 2000, Icarus, 143, 2

Boley A. C., Granados Contreras A. P., Gladman B., 2016, ApJ, 817, L17

Borucki W. J., et al., 2010, Science, 327, 977

Borucki W. J., et al., 2011, ApJ, 728, 117

Buchhave L. A., et al., 2012, Nature, 486, 375

Butler R. P., Marcy G. W., 1996, ApJ, 464, L153

Butler R. P., Vogt S. S., Marcy G. W., Fischer D. A., Wright J. T., Henry G. W., Laughlin G., Lissauer J. J., 2004, ApJ, 617, 580

Cáceres C., et al., 2014, A&A, 565, A7

Campbell B., Walker G. A. H., 1979, Publications of the Astronomical Society of the Pacific, 91, 540

Campbell B., Walker G. A. H., Yang S., 1988, ApJ, 331, 902

Charbonneau D., Brown T. M., Latham D. W., Mayor M., 2000, ApJ, 529, L45

Charbonneau D., Brown T. M., Noyes R. W., Gilliland R. L., 2002, ApJ, 568, 377

Charbonneau D., et al., 2009, Nature, 462, 891

Chen G., et al., 2018, A&A, 616, A145

Cooke B. F., Pollacco D., West R., McCormac J., Wheatley P. J., 2018, A&A, 619, A175

Croll B., Albert L., Jayawardhana R., Miller-Ricci Kempton E., Fortney J. J., Murray N., Neilson H., 2011, ApJ, 736, 78

Dressing C. D., Charbonneau D., 2013, ApJ, 767, 95

Fressin F., et al., 2013, ApJ, 766, 81

Fruth T., et al., 2012, AJ, 143, 140

Fruth T., et al., 2013, AJ, 146, 136

García Muñoz A., Schneider P. C., 2019, ApJ, 884, L43

Gilliland R. L., et al., 2011, ApJS, 197, 6

Gomes R., Levison H. F., Tsiganis K., Morbidelli A., 2005, Nature, 435, 466

Griffin R., 1973, MNRAS, 162, 243

Hasegawa Y., Yu T. Y. M., Hansen B. M. S., 2019, A&A, 629, L1

Hatzes A., Guenther E., Kürster M., 2003a, in EGS - AGU - EUG Joint Assembly. EGS - AGU - EUG Joint Assembly. p. 6093

Hatzes A. P., Cochran W. D., Endl M., McArthur B., Paulson D. B., Walker G. A. H., Campbell B., Yang S., 2003b, ApJ, 599, 1383

Heng K., Winn J. N., 2015.

Henry G. W., Marcy G. W., Butler R. P., Vogt S. S., 2000, ApJ, 529, L41

Howard A. W., et al., 2012, ApJS, 201, 15

Howell S. B., et al., 2014, PASP, 126, 398

Kabath P., Eigmüller P., Erikson A., Hedelt P., Rauer H., Titz R., Wiese T., Karoff C., 2007, AJ, 134, 1560

Kabath P., et al., 2009, AJ, 137, 3911

Kabáth P., Žák J., Boffin H. M. J., Ivanov V. D., Jones D., Skarka M., 2019, PASP, 131, 085001

Kabáth P., et al., 2020, PASP, 132, 035002

Kabáth P., et al., 2022, MNRAS, 513, 5955

Kane S. R., Vervoort P., Horner J., Pozuelos F. J., 2020, The Planetary Science Journal, 1, 42

Kaufer A., Stahl O., Tubbesing S., Nørregaard P., Avila G., Francois P., Pasquini L., Pizzella A., 1999, The Messenger, 95, 8

Kawauchi K., Narita N., Sato B., Kawashima Y., 2022, PASJ, 74, 225

Keles E., et al., 2019, MNRAS, 489, L37

Keppler M., et al., 2018, A&A, 617, A44

Kiefer F., 2019, A&A, 632, L9

Klagyivik P., et al., 2013, ApJ, 773, 54

Koubský P., Mayer P., Čáp J., Žďárský F., Zeman J., Pína L., Melich Z., 2004, Publications of the Astronomical Institute of the Czechoslovak Academy of Sciences, 92, 37

Kunimoto M., Matthews J. M., 2020, AJ, 159, 248

Lagrange A. M., et al., 2009, A&A, 493, L21

Landman R., Sánchez-López A., Mollière P., Kesseli A. Y., Louca A. J., Snellen I. A. G., 2021, A&A, 656, A119

Latham D. W., Mazeh T., Stefanik R. P., Mayor M., Burki G., 1989, Nature, 339, 38

Léger A., et al., 2009, A&A, 506, 287

Lin D. N. C., Bodenheimer P., Richardson D. C., 1996, Nature, 380, 606

Macintosh B., et al., 2015, Science, 350, 64

Marmier M., et al., 2013, A&A, 551, A90

Marois C., Macintosh B., Barman T., Zuckerman B., Song I., Patience J., Lafrenière D., Doyon R., 2008, Science, 322, 1348

Mayor M., Queloz D., 1995, Nature, 378, 355

Mayor M., et al., 2003, The Messenger, 114, 20

Mazeh T., Holczer T., Faigler S., 2016, A&A, 589, A75

Morbidelli A., Levison H. F., Tsiganis K., Gomes R., 2005, Nature, 435, 462

Mordasini C., Klahr H., Alibert Y., Benz W., Dittkrist K.-M., 2010, arXiv e-prints, p. arXiv:1012.5281

Moutou C., et al., 2013, Icarus, 226, 1625

Narita N., et al., 2019, Journal of Astronomical Telescopes, Instruments, and Systems, 5, 015001

Nascimbeni V., Piotto G., Pagano I., Scandariato G., Sani E., Fumana M., 2013, A&A, 559, A32

Nesvorný D., Morbidelli A., 2012, The Astronomical Journal, 144, 117

O'Conner Peluso D., et al., 2023, PASP, 135, 015001

Palle E., et al., 2017, A&A, 602, L15

Pasternacki T., et al., 2011, AJ, 142, 114

Pepe F., et al., 2021, A&A, 645, A96

Perruchot S., et al., 2011, in Shaklan S., ed., Society of Photo-Optical Instrumentation Engineers (SPIE) Conference Series Vol. 8151, Techniques and Instrumentation for Detection of Exoplanets V. p. 815115 (`arXiv:1110.2256`), doi:10.1117/12.892466

Pfalzner S., et al., 2015, Physica Scripta, 90, 068001

Queloz D., et al., 2001, The Messenger, 105, 1

Rauer H., et al., 2010, AJ, 139, 53

Rauer H., et al., 2014, Experimental Astronomy, 38, 249

Redfield S., Endl M., Cochran W. D., Koesterke L., 2008, ApJ, 673, L87

Ricker G. R., et al., 2015, Journal of Astronomical Telescopes, Instruments, and Systems, 1, 014003

Rivera E. J., et al., 2005, ApJ, 634, 625

Seidel J. V., et al., 2019, A&A, 623, A166

Seidel J. V., et al., 2020, A&A, 641, L7

Sing D. K., et al., 2011, A&A, 527, A73

Snellen I. A. G., Albrecht S., de Mooij E. J. W., Le Poole R. S., 2008, A&A, 487, 357

Struve O., 1952, The Observatory, 72, 199

Sullivan P. W., et al., 2015, ApJ, 809, 77

Tabernero H. M., et al., 2021, A&A, 646, A158

Triaud A. H. M. J., 2018, in Deeg H. J., Belmonte J. A., eds, , Handbook of Exoplanets. p. 2, doi:10.1007/978-3-319-55333-7˙2

Tsiganis K., Gomes R., Morbidelli A., Levison H. F., 2005, Nature, 435, 459

Tull R. G., MacQueen P. J., Sneden C., Lambert D. L., 1995, Publications of the Astronomical Society of the Pacific, 107, 251

Udry S., et al., 2007, A&A, 469, L43

Valencia D., Sasselov D. D., O'Connell R. J., 2007, ApJ, 656, 545

Vanzi L., et al., 2012, MNRAS, 424, 2770

Vítková M., 2020, Vliv kadence a rozptylu dat na přesnost určení parametrů exoplanetárních tranzitů [online], `https://is.muni.cz/th/uzyks/`

Walker G. A. H., Bohlender D. A., Walker A. R., Irwin A. W., Yang S. L. S., Larson A., 1992, ApJ, 396, L91

Walsh K. J., Morbidelli A., Raymond S. N., O'Brien D. P., Mandell A. M., 2011, Nature, 475, 206

Wang Z., Chakrabarty D., Kaplan D. L., 2006, Nature, 440, 772

West R. G., et al., 2019, MNRAS, 486, 5094

Wheatley P. J., et al., 2018, MNRAS, 475, 4476

Wittenmyer R. A., Tinney C. G., O'Toole S. J., Jones H. R. A., Butler R. P., Carter B. D., Bailey J., 2011, ApJ, 727, 102

Wittenmyer R. A., et al., 2016, ApJ, 819, 28

Wolszczan A., Frail D. A., 1992, Nature, 355, 145

Wright J. T., Marcy G. W., Howard A. W., Johnson J. A., Morton T. D., Fischer D. A., 2012, ApJ, 753, 160

Wyttenbach A., Ehrenreich D., Lovis C., Udry S., Pepe F., 2015, A&A, 577, A62

Wyttenbach A., et al., 2017, A&A, 602, A36

Ziegler C., et al., 2017, AJ, 153, 66

Žák J., Kabáth P., Boffin H. M. J., Ivanov V. D., Skarka M., 2019, AJ, 158, 120

von Essen C., Mallonn M., Hermansen S., Nixon M. C., Madhusudhan N., Kjeldsen H., Tautvaišienė G., 2020, A&A, 637, A76

A. Attachments

A.1 First Chapter publications

Publications supporting the first chapter:

- T. Fruth, P. Kabath et al 2012 AJ 143 140:
  Improved variable star search in large photometric data sets: New variables in CoRoT field LRa02 detected by BEST II
  `https://ui.adsabs.harvard.edu/abs/2012AJ....143..140F/abstract`

- P. Kabath et al. 2020, Publications of the Astronomical Society of the Pacific, Volume 132, Issue 1009, id. 035002, 12 pp. :
  Ondřejov Echelle Spectrograph, Ground Based Support Facility for Exoplanet Missions
  `https://ui.adsabs.harvard.edu/abs/2020PASP..132c5002K/abstract`

- S. Sabotta, P. Kabath et al. 2019, Monthly Notices of the Royal Astronomical Society, Volume 489, Issue 2, p.2069-2078
  Lack of close-in, massive planets of main-sequence A-type stars from Kepler
  `https://ui.adsabs.harvard.edu/abs/2019MNRAS.489.2069S/abstract`

- P. Kabath et al. 2022, Monthly Notices of the Royal Astronomical Society, Volume 513, Issue 4, pp.5955-5972 :
  TOI-2046b, TOI-1181b, and TOI-1516b, three new hot Jupiters from TESS: planets orbiting a young star, a subgiant, and a normal star
  `https://ui.adsabs.harvard.edu/abs/2022MNRAS.513.5955K/abstract`

A.2 Second Chapter publications

Publications supporting the second chapter:

- C. Caceres, P. Kabáth et al 2014, A&A, 565A, 7C
  Ground-based transit observations of the super-Earth GJ 1214 b
  `https://ui.adsabs.harvard.edu/abs/2014A%26A...565A...7C/abstract`

- P. Kabáth, J. Žák et al. 2019, Publications of the Astronomical Society of the Pacific, Volume 131, Issue 1002, pp. 085001:
  Detection Limits of Exoplanetary Atmospheres with 2-m Class Telescopes
  `https://ui.adsabs.harvard.edu/abs/2019PASP..131h5001K/abstract`

- J. Žák, P. Kabáth et al 2019, The Astronomical Journal, Volume 158, Issue 3, article id. 120, 8 pp. .:
  High-resolution Transmission Spectroscopy of Four Hot Inflated Gas Giant Exoplanets
  `https://ui.adsabs.harvard.edu/abs/2019AJ....158..120Z/abstract`

A.3 Other relevant publications

- M. Blažek, P. Kabáth et al. 2022: Constraints on TESS albedos for five hot Jupiters, Monthly Notices of the Royal Astronomical Society, Volume 513, Issue 3, pp.3444-3457 `https://ui.adsabs.harvard.edu/abs/2022MNRAS.513.3444B/abstract`
- Šubjak J. (w. Kabáth - supervisor) et al. 2020: TOI-503: The First Known Brown-dwarf Am-star Binary from the TESS Mission, The Astronomical Journal, Volume 159, Issue 4, id.151, 19 pp., `https://ui.adsabs.harvard.edu/abs/2020AJ....159..151S/abstract`
- Budaj J., Kabáth P., Pallé E. 2020: Extrasolar Enigmas: From Disintegrating Exoplanets to Exoasteroids, Reviews in Frontiers of Modern Astrophysics; From Space Debris to Cosmology, edited by Kabáth, Petr; Jones, David; Skarka, Marek. ISBN: 978-3-030-38509-5. Cham: Springer International Publishing, 2020, pp. 45-88, `https://ui.adsabs.harvard.edu/abs/2020rfma.book...45B/abstract`
- Sedaghati E. (w. Kabáth) et al. 2015: Regaining the FORS: optical ground-based transmission spectroscopy of the exoplanet WASP-19b with VLT+FORS2, Astronomy & Astrophysics, Volume 576, id.L11, 7 pp., `https://ui.adsabs.harvard.edu/abs/2015A%26A...576L..11S/abstract`
- Caceres C., Kabáth P. et al. 2014: Ground-based transit observations of the super-Earth GJ 1214 b, Astronomy & Astrophysics, Volume 565, id.A7, 9 pp, `https://ui.adsabs.harvard.edu/abs/2014A%26A...565A...7C/abstract`
- Bean J. Désert M., Kabáth P. et al. 2011: The Optical and Near-infrared Transmission Spectrum of the Super-Earth GJ 1214b: Further Evidence for a Metal-rich Atmosphere, The Astrophysical Journal, Volume 743, Issue 1, article id. 92, 12 pp, `https://ui.adsabs.harvard.edu/abs/2011ApJ...743...92B/abstract`.