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**MASTER THESIS**

Daniel Dupkala

# Outreach of an Exoplanet Research and the PLATO Space Mission in the Czech Republic

Department of Physics Education

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| Supervisor of the master thesis: | doc. RNDr. Zdeněk Drozd, Ph.D. |
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I would like to thank my supervisor doc. Zdeněk Drozd for his great support and motivation towards the work on my master thesis. Astronomy has always been my passion and I am grateful that I could share it with him. At first, I was worried about writing the thesis on the subject of outreach. Thanks to Zdeněk I was able to overcome it and put all of my passion for the exoplanets, the history of their research, and space exploration into this thesis.

Through the last couple of years, I have had many opportunities to promote astronomy and science as such and I am extremely grateful for each one of them. I have always appreciated talking about exoplanets to people who do not look up to the stars as much as I do. I hope my work with high school students has inspired at least some of them to pursue a career in science, as it has always been the main objective.

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Author: Daniel Dupkala

Department: Department of Physics Education

Supervisor: doc. RNDr. Zdeněk Drozd, Ph.D., Department of Physics Education

Abstract: The extrasolar planets have become one of the most exciting and promising research fields in modern astronomy. They could reveal the answers to some of the biggest questions such as the origin of life, planetary evolution, or the existence of extraterrestrial life in the universe. Exoplanets also present a unique option for scientific outreach as they are easy to imagine and understand. In this thesis, the current research, its history, and future plans are described with a focus on Czech participation in it. Especially the PLATO mission will give the Czech Republic a front seat in exoplanetary science. Various outreach activities are presented both conducted by the author and proposed for the future. A special focus was given to the work with talented high school students. Three activities were organized with the aim to present the research on the exoplanets to students and to give them the opportunity to try and participate in it. These activities covered the area of astronomical observations, the analysis of the light curves from the transit photometry, and finally the data processing of the stellar spectra for the radial velocity measurements. The activities were evaluated for future reference.

Keywords: Exoplanets, PLATO mission, Czech research, Outreach, High school students

# Contents

# Introduction

In 2019, the Nobel prize in Physics was awarded to Michel Mayor and Didier Queloz for “the discovery of the first exoplanets orbiting a solar-type star”, co-awarded to James Peebles for “theoretical discoveries in physical cosmology”[1]. The award for discovery from 1995 (Mayor and Queloz 1995 [64]) was a highlight of exoplanetary research which began decades prior to it (e.g. Wolszczan & Frail 1992 [119], Wolszczan 1994 [118], Struve 1952 [96] etc.) and grew even faster in last 30 years. Today it is one of the key astronomical research fields with many professional and amateur astronomers contributing to it. Both ground based observatories and space telescopes are used to look for new exoplanets as well as to study already-known planetary systems. The importance and general interest in the topic are demonstrated by the scale of planned missions dedicated to studying exoplanets. One of the most anticipated is the space mission PLATO expected to launch in 2026 [79].

There are several important reasons to study the extrasolar planets. At first, it is directly connected to the search for extraterrestrial life. The Earth-like planets are thought to be a natural home for various forms of life – from microbiological organisms to intelligent civilizations. This belief origins from the idea that if life is formed on the Earth, it can be formed on other planets with similar conditions as well. Therefore, the search for new exoplanets is targeted to Earth-size rocky planets orbiting the Sun-like stars. With the observational equipment and techniques getting more and more precise, we can study these exoplanets in detail and even observe the processes on their surface or in their atmosphere. This could lead to the discovery of extraterrestrial life.

A different reason – quite an important one for mankind – is to look for the next Earth where people could live. In approximately 5 billion years the Sun will die and for mankind, it will be necessary to travel and colonize a different planet in another stellar system. This may come even sooner as there are many possible reasons why the Earth could become uninhabitable. From the collapse of the climate system, draining of vital resources or the impact of the asteroid – any of this could be the cause for the migration to another planet. Of course, to colonize a new exoplanet, it is necessary to get there first. Our technology is not advanced enough to travel to even the nearest exoplanet – Proxima Centauri b (Anglada et al. 2014 [1]) – in a man’s lifetime. To travel the distance between the Earth and Proxima Centauri b, which is approximately 1.295 parsecs or $\approx 4.2$ light years (von Leeuwen 2007 [105]), it would take almost eight thousand years. That is with the travel speed of $163\,\mathrm{km\cdot s^{-1}}$ what is the speed record of the fastest space probe called Parker Solar Probe [41]. Other extrasolar planets with the ideal conditions are (or will be discovered) even further away. However, the search for them is important both scientifically and ideologically as it sets the goals for the research.

The third reason to search for and study exoplanets is to understand our planetary system, its evolution and even the origin of life. Since physics laws are the same in the whole universe, what we learn about the planets outside of the Solar system we learn about the Earth and our Solar system as well. We can

[1] https://www.nobelprize.org/prizes/physics/2019/summary/

observe and study stellar systems with planetary companions at different stages of development. The big interest is in the formation of Earth-size rocky planets and their atmospheric and climate conditions. As the observational techniques get more precise, the possibility to observe and study the extrasolar moons and comets rises. We can study for example the role of giant gas planets in the cleaning of the planetary system of small bodies and asteroids, which can pose a threat to a newly originated life on an exoplanet.

The extrasolar planets have a huge outreach potential as well. It is still a relatively new research field with many questions yet to be answered. It studies "the big questions" of life and our place in the universe, what naturally attracts the public interest. The results are simple to understand and easy to imagine. The popularity of a science-fiction genre in the 21st century[2] and variety of artistic impressions depicting new exoplanets helped significantly. Generally, exoplanets are an easy gateway to science for young students – future scientists and their teachers, families and friends (i.e. for the general public). Public interest in the topic (and science as such) is important for its future development (through funding and general support).

This thesis aims to summarize the current research, describe its methods and present the next steps in the field of exoplanetary science, mainly the space mission PLATO. It focuses especially on the research in the Czech Republic and the Czech contribution to the PLATO mission. It presents various outreach activities connected to the topic of exoplanets both for students (mainly high school students) and the general public. Some of these activities are intended as a general popularization of astronomy while others are specifically targeted to students with a possible interest in a further study of the field. One of the aspects was to process the real data with the students so they can directly try out the scientific work. For this purpose, interactive materials were prepared.

[2] Good example of recent high popularity of sci-fi genre is the list of the most grossing movies, where the two leading movies are sci-fi and 7 out of the first 10 are sci-fi movies as well, all produced in the last 14 years (Wikipedia: List of highest-grossing films [114]).

# 1. History of the exoplanetary research

## 1.1 Pre-discovery research

### 1.1.1 Early history

Even though the first discoveries of exoplanets were made in the last decade of the 20th century, the idea of other planetary systems originated long before that.

In the 5th century BC, the known universe was limited to the Earth (already known to be round) and its atmosphere, the Sun and the Moon, five planets (Mercury, Venus, Mars, Jupiter, and Saturn), and the sphere of stars. Observational astronomy was already quite precise at that time, e.g. a Greek mathematician, astronomer, and philosopher Thales of Miletus (626/623 – 548/545 BC) correctly predicted a total Solar eclipse in 585 BC (Wikipedia: Thales of Miletus [117]). Yet the correct scheme of the Solar system was still widely unknown. Despite that, ancient philosophers had various hypotheses about the universe and its vastness.

The first one, who mentioned the thoughts of different "worlds" was the Greek philosopher Democritus of Abdera (460 – 370 BC). He did not think of exoplanets directly, but he did imagine there are numerous solar systems in the universe, some of them similar to our Solar System, others very different with no Sun and Moon, some of them larger, some smaller (Čeman and Pittich: Slnečná sústava [16], Kolinski [50]). He thought some of these worlds are inhabited by living creatures or plants. Epicurus (341 – 270 BC), another Greek philosopher, influenced by the ideas of Democritus presented the idea of an infinite number of worlds [50]. These ideas are known as cosmic pluralism. Around the same era, Aristarchus of Samos (310 – 230 BC) introduced the heliocentric model of the Solar system, which takes off the Earth from the pedestal [16].

However, all these brave new ideas were to be forgotten with the fast spreading of the philosophy of the great philosopher Aristotle (384 – 322 BC) [16]. He was a good speaker with strong political influence, hence he could assert his own views. These were rather conservative thoughts of a single geocentric world with the Earth in the absolute center of it and the stars not considered to have their own worlds. Unfortunately, Aristotle's ideas prevailed for a very long time. They were further developed by several philosophers and astronomers, completed by Ptolemy (100 – 170 AD) in the astronomical treatise called the Almagest [16]. Ptolemy's description of the world, supported by his precise observations and stellar maps became the basis of astronomy for many centuries (with several stellar constellations recognized and included in today's maps as well).

The change came in the 16th century. At first, a Polish astronomer Nicolaus Copernicus (1473 – 1543) came up with his heliocentric Solar system. However, his theory had not been accepted yet. Another philosopher and cosmologist, an Italian friar Giordano Bruno (1548 – 1600) described correctly that the Milky way – a light belt visible on a dark night sky – is the light from thousands and thousands of stars similar to our Sun [16]. He said that each one of these stars has a world with planets like our Sun (Bruno divided objects into "suns" and "earths", probably becoming the first one to claim that stars are the same objects as our Sun). He brought back the ideas of cosmic pluralism, stating many of the outside worlds are inhabited by animals or humans. He also suggested the universe is infinite with an infinite amount of "suns" (Wikipedia: Giordano Bruno [112]). For proclaiming these ideas, Bruno was imprisoned and tried by the Roman Inquisition. He was found guilty of heresy and executed by burning, with his tongue nailed with a wooden nail[1] [16], [112].

In 1609, Galileo Galilei became the first one to use the telescope, a new invention of German-Dutch spectacle-maker Hans Lipperhey (1570 – 1619), for the night sky observations [16]. He explored most of the known objects of the Solar system, discovering the Solar spots, the rings of Saturn (even though he could not explain them at the time), Jupiter's four largest moons (which now bear his name), phases of Venus, etc. He came to the correct conclusion that his observations are proof of the Copernicus heliocentric system. These findings were confirmed by the calculations of Johannes Kepler (1571 – 1630), a German astronomer and mathematician. Based on precise visual observation of Tycho Brahe (1546 – 1601), he formulated his laws[2] of planetary motion [16]. Kepler's laws say that planets orbit around the Sun on elliptical orbits. These laws are together with Newton's gravitational law bases[3] of the celestial mechanics used to characterize any stellar or planetary system.

These discoveries meant a huge step forward in astronomy and astrophysics. The telescope observation helped to understand the role of the Solar system in space and proved that the Sun is no different from other stars in the universe. With the improvements in telescopes, astronomers could study planets and stars more closely. Again the thought of stars having planets orbiting them was raised by many astronomers. Christiaan Huygens (1629 – 1695), who made several discoveries in planetary sciences, such as describing Saturn's rings, suggested using observational instruments for studying these planets (Kolinski [50], Sagascience [10]). Bernard le Bovier de Fontenelle (1657 – 1757) wrote an essay on cosmic pluralism, stating stars are suns giving light to its worlds (planets) [10]. The existence of distant planets became step by step the question of astronomy and not just philosophy. However, it took more than two centuries to finally discover the first extrasolar planets. Since the exoplanets are too faint to be observed visually with the use of small telescopes, new observational methods, such as photometry or stellar spectroscopy, had to be developed. The observational instruments had to improve as well.

[1] It is uncertain what was the main reason for Bruno's death sentence. Some historians think it was his cosmological view of the world. However many others disagree and assume it was his theological claims which decided his fate [112].

[2] Kepler formulated the first two laws in 1609, published in *Astronomia Nova*. The third law was published in *Harmonices Mundi* later in 1619. These laws applied not only to planets in the Solar system but to Jupiter's four largest moons as well, what was noted by Kepler in 1921 (Wikipedia: Kepler's laws of planetary motion [113]).

[3] Isaac Newton (1643 – 1727) formulated his gravitational law in 1687 in the work called *Principia mathematica philosophiae naturalis* [16].

### 1.1.2 The 20th century

In the first half of the 20th century, two huge discoveries were made by an American astronomer Edwin Powell Hubble (1889 – 1953), working at the Mount Wilson Observatory in California. Hubble was using the 2.5 m Hooker telescope which was the world's largest telescope back in the day (it held the position from its completion in 1917 until 1949) [116]. In 1924, Hubble discovered the Andromeda Nebula is a galaxy itself, not part of our Galaxy. He came to this conclusion thanks to the precise measurements of the Cepheid variable stars of the Andromeda Nebula, which were located too far to be part of our Galaxy (Čeman and Pittich: Slnečná sústava [16]). Later, Hubble studied more nebulae to find more of them are distant galaxies. He measured the distances of 24 galaxies and examined their radial velocities. In 1929, from these measurements, made with Milton Humason, he discovered that most of the galaxies are moving away, with the speed of this movement being higher with the greater distance between them (Wikipedia: Edwin Hubble [110]). This became the proof of expansion of the universe. Both discoveries had a big impact on our understanding of the universe and our place in it[4].

Although, it is necessary to state Hubble was not the first one who brought the idea of the universe expanding. In 1927, two years before Hubble's findings, a Belgian Catholic priest, theoretical physicist, and astronomer Georges Lemaître published a work explaining the expanding universe. He was also the first to derive Hubble's law, which was recently re-named Hubble-Lemaître law by the IAU[5] and proposed the Big Bang theory about the origin of the universe.

The 2.5 m Hooker telescope, which Hubble used for his observations, made another observation historically significant in the field of exoplanets. However, this was found only recently. In 1917, astronomer Adriaan van Maanen found a faint star [106]. He found it thanks to its subtle motion and considered it to be an F-type star due to the presence of heavy elements in its absorption spectrum (Figure 1.1). Today it is called the van Maanen's Star and it is the first polluted white dwarf to be identified. The abundant presence of heavy elements indicates that some interstellar medium is falling into the star's atmosphere polluting its spectrum. These elements could not have been created inside the star because of its gravity which would pull them down toward the star's center. Since the white dwarf is a very old star this interstellar medium could be a remnant of the exoplanetary system.

As Farihi summarized in 2016 [28] the absorption lines visible in Van Maanen observations may point out to the presence of an exoplanet. As several studies showed (e.g. Zuckerman et al. 2007 [122]) the material falling into the atmosphere of the star (causing the pollution of the spectrum) was previously a part of a large asteroid or group of asteroids with a chemical composition similar to the Earth and the Moon. Even more, it could have been a part of a larger object - possibly a terrestrial planet. Latest studies show the "falling" of the material cannot

[4]The size of the known universe increased from the Solar system in later centuries to the whole Galaxy and then, thanks to the Hubble, it expanded even further from a single Galaxy to the space "full of them". Furthermore, thanks to Hubble's discovery we learned the whole universe is expanding.

[5]IAU press release from October 29, 2018, accessible at `https://www.iau.org/news/pressreleases/detail/iau1812/` (retrieved on December 3, 2022).

be spontaneous, indicating many of the polluted white dwarfs have extrasolar planets causing this motion (Veras et al. 2018 [107]). Therefore, van Maanen's spectra could be the first record of the exoplanet observation, as pointed out by Zuckerman in 2014 [121] (even though the planet itself has not been detected yet)[6].

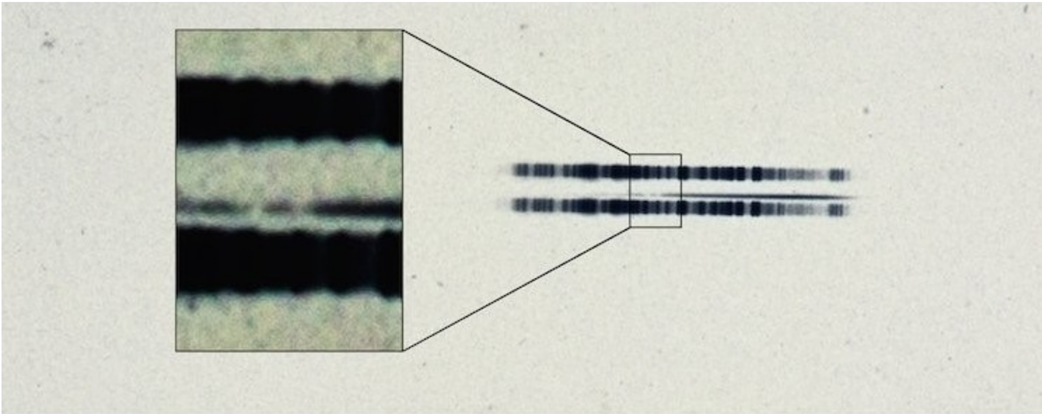

Figure 1.1: Close-up look on the stellar spectrum of the van Maanen Star observed by Adriaan van Maanen in 1917. There are visible two absorption lines of the same calcium ion referring to the presence of heavy elements. This spectrum is possibly the first observational record of an extrasolar planet. Image taken from [28] credited to Carnegie Institution for Science.

In the 20th century, many studies were focused on binary systems using both spectroscopic and photometric methods. Thanks to the radial velocity measurements or transit observations done by photometry, several systems containing planet-like objects were described. Unfortunately, no confirmation of the existence of an extrasolar planet was made. In 1952 Otto von Struve [96] wrote a paper on the topic, describing the possibility of exoplanet detection using observation instruments available back in the day. He calculated the feasibility of detecting a hot Jupiter-sized planet using the radial velocity method. Results of von Struve's calculated radial velocity oscillations were in the range of $\pm 200\,\mathrm{m{\cdot}s^{-1}}$. He suggested the transits may occur as well and compared the precision of photometry to the RV method. He came to the conclusion the RV method would be more precise, but the photometry could be used for fainter stars.

In the 1980s Bruce Campbell and Gordon Walker made huge progress in radial velocity measurements. They developed a very precise method using an absorption cell. Hydrogen fluoride was used to generate a reference absorption line in stellar spectra from a coudé spectrograph. The accuracy they reached was about $15\,\mathrm{m{\cdot}s^{-1}}$ (Campbell & Walker 1979 [14]).

A huge debate surrounded the data published by Peter van Kamp. Since 1938 he has been observing Barnard's Star[7]. Using the method of astrometry he

[6] Nice article summarizing the discovery can be found at NASA/JPL web pages from November 1, 2017, at `https://www.nasa.gov/feature/jpl/overlooked-treasure-the-first-evidence-of-exoplanets` (retrieved on Nov 25, 2022).

[7] Barnard's Star is the 4th closest star to the Solar system. Its distance from Earth is about six light years. It is well known as the star with the highest proper motion with a value of $10,3$ arcseconds per year relative to the Sun (Wikipedia: Barnard's Star [109], Simbad database [4]).

was looking for the periodic swinging of the star on photographic plates. In the 1970s, after decades of observation, he found a wobble in the star's movement [50]. Results of the follow-up calculation indicated the wobble was caused by extrasolar planets. Its mass was estimated to be 1.6 times the mass of Jupiter, later calculations gave the result of two extrasolar planets with masses of 0.7 and 0.5 respectively.

Van Kamp's claims had been accepted by astronomers until 1973 when two different papers were published about Barnard's Star planetary companion. The observations done at the same observatory as van Kemp was working at – the Sproul Observatory at Swarthmore College – explained the star wobble as a systematic error connected with the process of production of the photographic plates (Hershey 1973 [40]). Using newer instrumentation at a different observatory the star observations failed to verify any planetary companion (Gatewood & Eichhorn 1973 [32]). In a research published in 2018, astronomers have opened the dispute about the exoplanet orbiting Barnard's star once again presenting a super-Earth candidate (Ribas et al. 2018 [85]). Yet again several studies marking the discovery as a false positive came up soon after (Lubin et al. 2021 [60], Artigau et al. 2022 [2]). Today, the general opinion assumes there are no exoplanets of the Barnard's Star.

## 1.2 The first discoveries and early research

There were several unconfirmed records of exoplanet detections at the turn of the 1980s and 1990s. In a paper from 1988 two stars – Chi$^1$ Ori A[8] and Gamma Cep – were observed with large RV variations indicating possible planetary companions (Campbell et al. 1988 [15]). Similar results were published a year later concerning the Gamma Cep star (Lawton & Wright 1989 [56]). However, due to the high uncertainty, the discovery was not confirmed until 2002 (Hatzes et al. 2003 [36]). Over time the parameters of exoplanet were specified, describing the stellar system Gamma Cep as a binary system of an orange giant or subgiant and a red dwarf companion with an extrasolar planet of the mass of $9.4\,\mathrm{M_J}$[9] (Benedict et al. 2018 [5]).

Another exoplanetary candidate was orbiting star HD 114762. Discovered in 1989 (Latham et al. 1989 [55]) it was considered to be a brown dwarf or a giant planet. Several studies supported the speculations of its planetary nature, mostly because of the minimal mass of $11\,\mathrm{M_J}$. However, in 2019 the true mass was determined to be much greater, pushing the object out of the planetary limits (Kiefer 2019 [49]).

The first confirmed discovery of an extrasolar planet was made in 1992. It came as quite a surprise to the scientific community. Not only two exoplanets were found at once, but they were also discovered orbiting a dead star – the millisecond pulsar PSR B1257+12[10]. The discovery was made by Aleksander

[8]The star is a confirmed binary system with no confirmed exoplanets (Wikipedia: Chi$^1$ Orionis, retrieved on Nov 25, 2022, from `https://en.wikipedia.org/wiki/Chi1_Orionis`).

[9]Data obtained with NASA/ESA Hubble Space Telescope astrometry [5].

[10]The pulsar was previously designated PSR 1257+12 with alternative designation PSR J1300+1240 (Wikipedia: PSR B1257+12, retrieved on November 26, 2022, from `https://en.wikipedia.org/wiki/PSR_B1257%2B12`).

Wolszczan and Dale Frail through the study of the pulsar's timing variations. From the irregularity of its pulses, they concluded two planet-like objects are orbiting the pulsar (Wolszczan & Frail 1992 [119]). Astronomers expected to find the exoplanets orbiting the main sequence stars according to the planetary formation models similar to the Solar system models. However, the pulsar is a dead star – a neutron star with a fast rotation generating a very strong magnetic field. The exoplanets were created probably in the secondary planetary formation after two white dwarfs merged together into the pulsar (Podsiadlowski 1993 [82]), even though it has not been confirmed yet.

The discovery was soon confirmed and in 1994 the third planet was detected in the pulsar system (Wolszczan 1994 [118]). All three exoplanets are terrestrial. The first two discovered planets have masses estimated to $4.3\,\mathrm{M}_{\oplus}$ and $3.9\,\mathrm{M}_{\oplus}$ (Konacki & Wolszczan 2003 [51]). They orbit the star in a distance of 0.36 AU and 0.46 AU respectively. The third one has an orbit with a semi-major axis of 0.19 AU from the parent star. With the estimated mass $0.02\,\mathrm{M}_{\oplus}$ it is considered to be the least massive planet characterized [11] [51].

In 1995, soon after the Wolsczcan and Frail's discovery the first exoplanet orbiting the main sequence star was discovered. Using the method of radial velocity measurements Michel Mayor and Didier Queloz of the University of Geneva discovered an exoplanet orbiting the star 51 Pegasi (Mayor and Queloz 1995 [64]). The planet is a gas giant with the orbital semi-major axis only 0.0527 AU. The discovery was quite surprising, as the planet is orbiting very close to the parent star. It was assumed that the gas giants are formed further away from the star as the light elements are blown away due to the stellar wind. Therefore, 51 Pegasi b is the first representative of the group of hot Jupiter planets – gas giants orbiting close to the star. The existence of the planet was confirmed just a few weeks after by other teams (Mayor et al. 1995 [65], Marcy et al. 1997 [61]). As stated before, for this discovery Mayor and Queloz were awarded the 2019 Nobel Prize in Physics.

Soon after the first discovery, many more detections of exoplanets were announced. In the following years, several exoplanets were found in the data from previous observations (e.g. the discovery of 47 Ursae Majoris b, Butler & Marcy 1996 [12]). At first, there were just a few discoveries per year. As for the interesting fact, 1997 was the last year, when no new extrasolar planet was discovered. However, the numbers began to increase rapidly.

The first discoveries were made by pulsar timing and radial velocity measurements. These methods are reliable, yet using only the RV measurements it is not possible to calculate the exact mass of the exoplanet (see the chapter 2). Therefore, astronomers were trying to detect an exoplanet transit using photometry. The first successful attempt was made in 1999 when the transit of previously known exoplanet HD 209458 b was detected (Henry et al. 2000 [39], Charbonneau et al. 2000 [17]). The planet is a hot Jupiter with an orbital period of approximately 3.5 Earth days. It orbits a Sun-like star (spectral type F9V) located in the Pegasus constellation (same as 51 Pegasi b), approximately 150 light years away from the Earth. The star is an easy target for its relative brightness

[11] According to the NASA Exoplanet Archive, retrieved on November 26, 2022, from `https://exoplanetarchive.ipac.caltech.edu/cgi-bin/TblView/nph-tblView?app=ExoTbls&config=PSCompPars`

(apparent magnitude 7.63 in the V band – visual, Simbad database [37]).

The exoplanet itself was discovered several months before the transit detection (Henry et al. 1999 [38]). It has gained a prominent position among the known extrasolar planets because of many records connected to its research. In 2001, astronomers found a signature of planetary atmosphere in the stellar spectra of its parent star (Charbonneau et al. 2002 [18]). Therefore, HD 209458 b became the first known exoplanet with a detected exo-atmosphere. The discovery was made from data obtained with the Hubble Space Telescope.

Other interesting findings were presented in the following years. It was discovered the hydrogen atmosphere of the planet is evaporating as a result of a close orbit to the star. Also, there were found oxygen and carbon in its atmosphere, making it "the first" again (Ehrenreich et al. 2008 [26]). In light of new theoretical models, it is alleged to have water vapor in its atmosphere. This would mean HD 209458 b would be the first exoplanet with water vapor detected. The hypothesis was later supported by several studies (Tinetti et al. 2007 [101]). This exoplanet was also one of the first two exoplanets – the second one being HD 189733 b – whose spectra were directly detected (Richardson et al. 2007 [86]). HD 209458 b paints a good picture of the progress of the exoplanetary research as it shows a continuing characterization on a more and more detailed level.

After the first discoveries, the number of known exoplanets was rapidly increasing. At the beginning of the 2000s tens of new exoplanets were being discovered a year. Many multi-planetary systems were detected, such as Upsilon Andromedae. It is the first exoplanetary system discovered orbiting a main sequence star. It consists of three exoplanets discovered in 1996 (planet b) and 1999 (planets c and d) (Ligi et al. 2012 [59]). Soon, with the use of new technologies and methods and especially with the use of space telescopes (see sub-chapter below), the number of new exoplanets became increasing by hundreds a year (Figure 1.2). Recently, a huge milestone was met as the 5000th exoplanets was confirmed[12]. As of December 3, 2022, 5292 exoplanets are discovered in 3903 planetary systems (with 848 multiple planetary systems)[13].

### 1.2.1 Nomenclature

The International Astronomical Union (IAU) decided to use a naming technique similar to the naming of a multi-star system. The name of the exoplanet consists of its parent star's name – for simple identification. To the name a lowercase letter is added, starting with the letter *b* as the letter *a* is designated for the parent star itself. The letters are assigned in the order of discovery. When multiple exoplanets are detected at once, the letters are assigned in order of distance from the parent star, with the closest exoplanet designated with the lower letter. Lately, the IAU started a campaign for naming the exoplanets the proper names (see the chapter 4).

[12] Published by the NASA/JPL on March 21, 2022, retrieved on December 3, 2022, from `https://www.jpl.nasa.gov/news/cosmic-milestone-nasa-confirms-5000-exoplanets`

[13] Based on the data from exoplanet.eu database, retrieved on December 3, 2022, from `http://www.exoplanet.eu/catalog/`

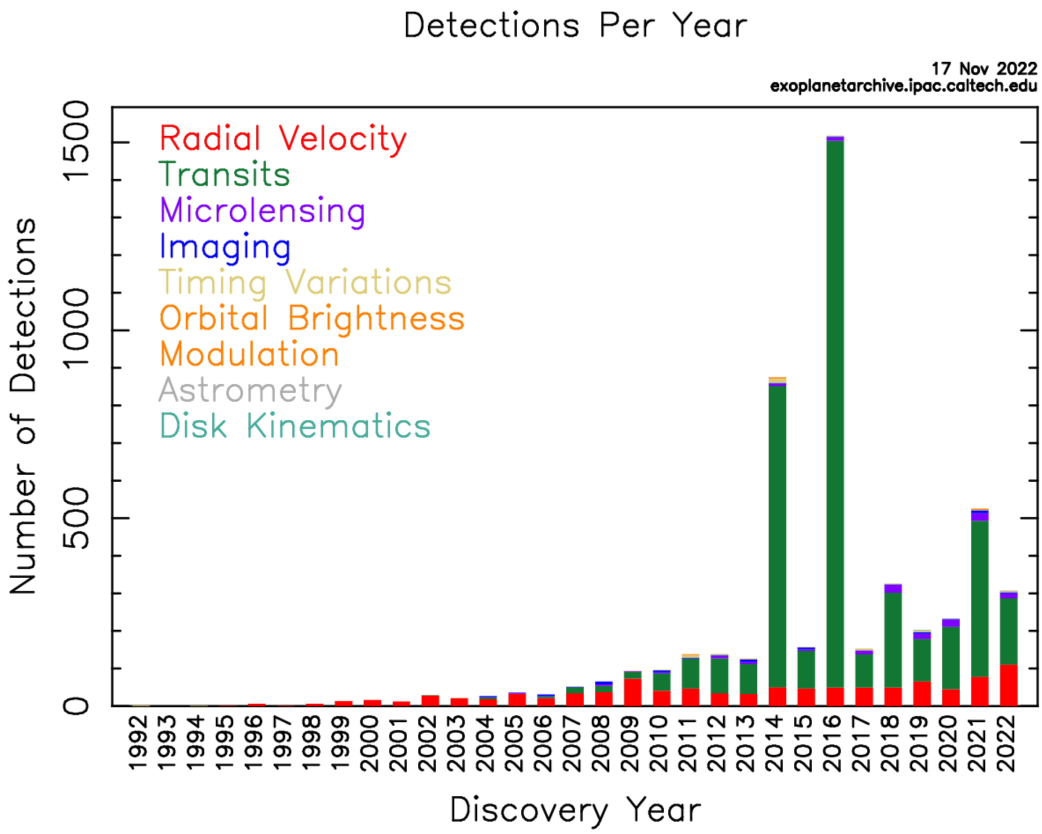


Figure 1.2: Number of discovered exoplanets per year with the specified detection method. Image credits to NASA Exoplanet Science Institute (Exoplanet plots, retrieved on November 27, 2022, from `https://exoplanetarchive.ipac.caltech.edu/exoplanetplots/` [70]).

## 1.3 An era of the space telescopes

Naturally, space telescopes have a huge advantage in comparison to ground based observatories. Not only they can be used at any time of the day, but they also are not affected by the Earth's atmosphere and its effects such as weather conditions and light or dust pollution. Thanks to this, we can get more observational hours from them and even get the data not obtainable from the observatories located down on the Earth. Space telescopes are used for ultraviolet, X-rays, and gamma rays observations which are blocked by the upper atmosphere. Infrared wavelengths are mostly absorbed by the lower atmosphere so infrared observations can be made only from high-altitude ground based observatories or space telescopes. Observations in these wavelength regions are essential for studying the exoplanets as they provide important additional information.

Space telescopes were used for exoplanetary research from the beginning. The Hubble Space Telescope was used for several major discoveries, such as the first detection of the exo-atmosphere of planet HD 209458 b (Charbonneau et al. 2002 [18]). It helped with a more delicate characterization of exoplanets (e.g. Benedict et al. 2006 [6]). Hubble's observations helped to detect oxygen in the atmosphere of exoplanet HD 189733 b (Ben-Jaffel & Ballester 2013 [7]) and calculate its albedo, determining the planet has a deep blue colour (Evans et al. 2013 [27]).

Quite famous are Hubble's images of Fomalhaut, the brightest star of the constellation Southern Fish (lat. Piscis Austrinus). The young star has several debris disks. In one of these disks, astronomers have spotted an object which they have assumed was an exoplanet (as shown in Figure 1.3). These images were considered to be the first direct images of an extrasolar planet ever taken (Kalas et al. 2008 [47]). Later studies have questioned this conclusion. Researchers agree on the existence of Fomalhaut b, yet its nature is still not exactly determined (Currie et al. 2012 [22], Pearce et al. 2021 [76]). Several studies discuss the possibility of a planet with a very eccentric orbit hidden inside a layer of dust and debris. A different explanation indicates a remnant of a planetary or asteroid collision that occurred in the last 50-150 years (Galicher et al. 2013 [30], Gaspar & Rieke 2020 [31]).

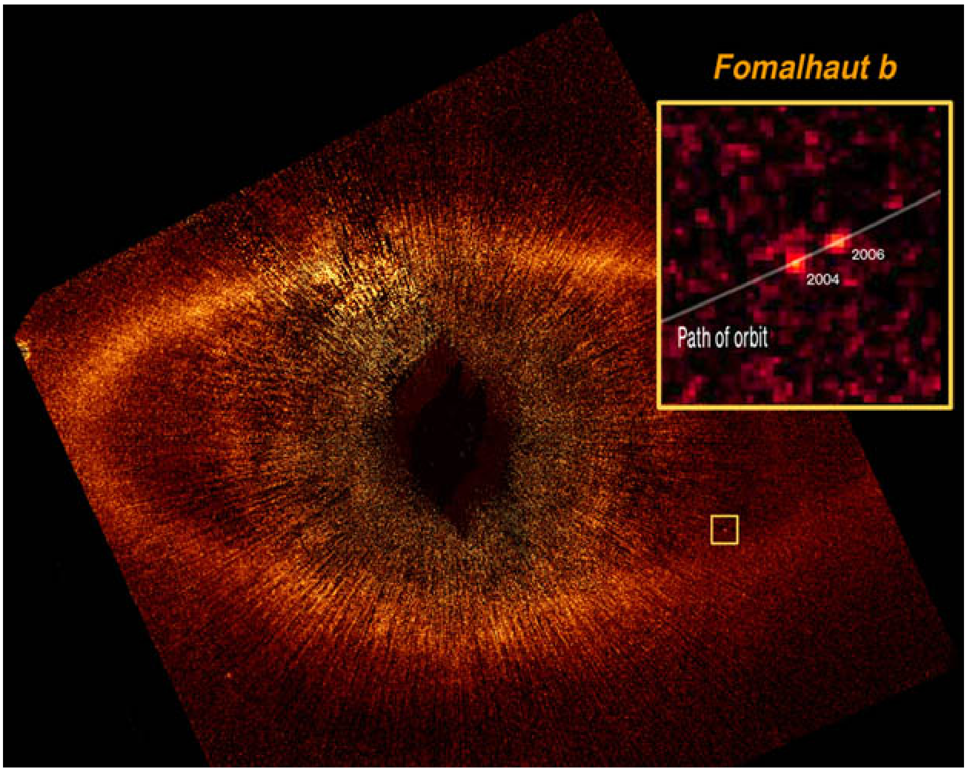


Figure 1.3: Fomalhaut images taken with the Hubble Space Telescope. An object initially considered to be an extrasolar planet is visible in the debris disks. Image credits to Paul Kalas/NASA/ESA.

The Spitzer Space Telescope made a big impact even though it was not primarily dedicated to exoplanetary research. The telescope observing the infrared part of the spectra discovered and studied several Earth-like exoplanets. With precise observations, it helped to determine important parameters and characteristics (e.g. Nutzman et al. 2009 [74]). Among those worth mentioning, the telescope was used for the transit detection of HD 219134 b, a close-to-Earth rocky planet. (Motalebi et al. 2015 [68]). The Spitzer Space Telescope is also credited for discovering and detailed studying five new exoplanets in the multi-planetary system TRAPPIST-1 (Gillon et al. 2017 [33]). Two planets have been discovered previously in the system with one additional planet unconfirmed. Thanks to the Spitzer observations this third planet was revealed to be multiple planets. It is one of the greatest scientific contributions Spitzer has made.

The first space telescope mission dedicated primarily to exoplanet research was the French-led mission CoRoT. The French government space agency (CNES) cooperates on the mission with ESA and other partners. Using the method of transit photometry, it was set to look for exoplanets with short orbits with a special aim for large terrestrial planets (Baglin et al. [3], Monteiro et al. [67]). Alongside the photometry, CoRoT was used for the research of astroseismology as it studied the stellar pulsations of Sun-like stars. The mission was launched in 2006 and it was used until 2013 when it ended due to a malfunction. In general CoRoT mission was a huge success. It helped to discover around 30 exoplanets. Among them is a planet marked as CoRoT-7b which was discovered in 2009 (Léger et al. 2009 [58]). It was the smallest super-Earth planet known when discovered with a measured radius. CoRoT was a pioneer and the experience gained by the mission paved a way for new and more advanced telescopes.

Ground-breaking progress in the research of extrasolar planets has been made by the Kepler space telescope. It was launched by NASA in 2009 and its primary mission was planned for three and half years. It was orbiting the Sun on a heliocentric orbit and its semi-major axis was similar to the Earth's. The telescope is of the Schmidt type with a primary mirror of diameter $0,95$ meter. Its focal plane camera is made of 42 CCD chips with the field of view $10° \times 10°$ (Caldwell et al. 2010 [13]).

Like CoRoT, Kepler was using photometric observations to detect transiting exoplanets (Borucki et al. 2016 [8]). However, Kepler was designed for long-term observations. It was set to observe a particular field of view for the whole duration of the mission with the plan to detect terrestrial exoplanets similar to the Earth in terms of orbital parameters and habitability. For a planet with an orbital period of about a year, it gives more than one detection per mission duration, providing important orbital parameters. With the fixed field of view (FOV) with a diameter of circa 12° it was continuously observing more than 170000 stars at the same time[14].

In 2013, two out of four reaction wheels had a malfunction. With limited stabilization options, the mission had to be rearranged. The telescope used solar wind for stabilization at the orbit. This method gave Kepler a stable FOV for approximately 80 days after which it was directed to the next target FOV for another time interval. Kepler's second mission was named K2 and it started in 2014. During the mission operations, a total of 19 scientific observation campaigns took place. K2 mission ended in October 2018 after the telescope run out of fuel.

Despite the reaction wheels' failure, Kepler/K2 mission was a huge success. During nine years of operation, Kepler observed more than 500000 stars. It is discovered more than 5000 candidates from which more than 3250 candidates have been confirmed. More than 300 candidates are yet to be confirmed.

Actually, the process of confirmation of exoplanets has not been optimized perfectly for ground based observatories. As the false positivity rate is quite high for Kepler candidates, it is necessary to confirm the discovery of exoplanets with other observations, usually done with a different observational method at the ground based observatories. Kepler was able to observe quite faint stars ranging approximately from 9 mag to 16 mag. This is too faint for many small meter-

[14]Kepler's target FOV was located in the northern sky hemisphere in the constellations of Cygnus, Lyra and partially Draco

sized class telescopes. Insufficient capacity to confirm the candidates resulted in the fact there are almost as many unconfirmed candidates as the confirmed exoplanets discovered by Kepler today. Many already confirmed exoplanets are not fully characterized (meaning their basic parameters such as mass, radius, density, and orbital parameters are not determined yet).

Thanks to Kepler's findings, a new mission TESS (Transiting Exoplanet Survey Satellite) was designed to prevent these problems. NASA has set several basic parameters to increase the capabilities of ground based observations. The target stars are brighter with the apparent magnitude range starting at 4 or 6 mag and reaching up to 13 mag. Primary targets are the red dwarfs or main-sequence stars, i.e. spectral type from F5 to M5 (Ricker et al. 2015 [88]). This achieves easier and more precise follow-up observations using even meter-sized telescopes. Stellar spectra of F5 to M5 stars provide more spectral lines as well, helping to obtain precise radial velocity measurements. The rotation of young stars, absence of spectral lines, or high brightness, make spectral analysis problematic, inaccurate, or near impossible (especially for smaller telescopes). The red dwarfs and Solar-type stars are expected to have better conditions for the formation of habitable exoplanets (because of the less radiation etc.). Most of the exoplanets are expected to be found near the Solar system at distances shorter than 300 ly.

TESS scans an area almost 400 times larger than Kepler. It has four CCD cameras and all of them have the same field of view $24° \times 24°$ [88]. They are set in the straight line configuration one under the other achieving combined FOV $24° \times 96°$ (as shown in Figure 1.4). The ecliptic sphere is divided into the northern and southern hemispheres, both divided into 13 sectors (in total 26 sectors). Each sector is observed for 27 days, then the target FOV is moved to the next sector. Some parts of the sectors are overlapping with the poles being observed in all sectors for long-period exoplanet detection. After all, sectors observed on one hemisphere, TESS moves to the other one[15]. The primary mission was planned for two years, after which TESS repeats the cycle.

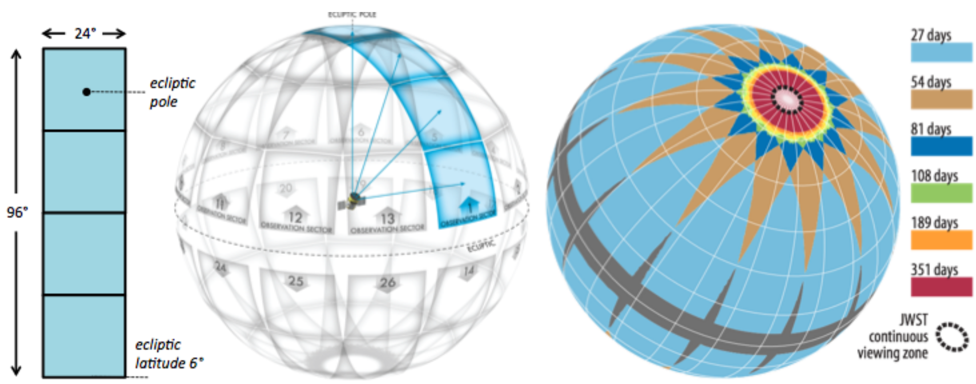


Figure 1.4: TESS field of view and the night sky coverage. Image taken from Ricker et al. 2014 [87].

The mission launched in April 2018 with the first light taken the same year in August. As of December 10, 2022, TESS discovered more than 6000 candidates

[15]TESS began observation on the southern hemisphere.

from which 276 were confirmed and almost 4100 are yet to be confirmed. The rest of the candidates were identified as false positives (NASA Exoplanet Science Institute, [70]).

The candidates (or even some confirmed exoplanets) are then observed by the ground based observatories, some of them are also provided as the targets for follow-up observations by the James Webb Space Telescope (JWST). Successor to the Hubble Space Telescope was launched at the end of 2021 and its already making huge discoveries, such as the identification of carbon dioxide in the atmosphere of the exoplanet WASP-39b (The JWST Transiting Exoplanet Community Early Release Science Team 2022 [99]).

Next in the line of the space probes designed to study exoplanets is the ESA mission PLATO (PLAnetary Transits and Oscillations of stars, Figure 1.5). This space telescope is planned to be launched in 2026. However, there have been several setbacks as the mission was rescheduled from previous years. As with the previous missions, PLATO will search for the transits of exoplanets orbiting Sun-like yellow dwarf stars, red dwarfs, and subgiant stars. It is planned to study up to million stars (PLATO Definition study report, ESA 2017 [79]). The space probe will be carried to the L2 Lagrange point, which is situated on a line from the Sun to the Earth, behind the Moon. The development of the PLATO mission is connected to the Czech Republic, which will be described later in chapter 3.

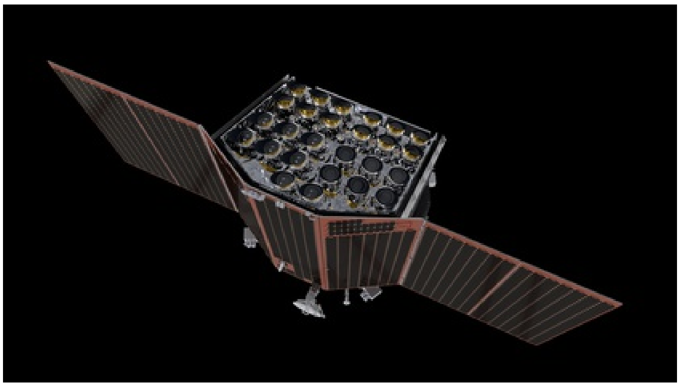

Figure 1.5: Rendering of the PLATO spacecraft in a fully deployed state. Image credits to ESA.

# 2. Methods of the exoplanetary research

In this chapter the most important methods for exoplanetary research are described[1]. All the data on the numbers of the detected exoplanets and their detection methods are based on data from NASA Exoplanet Archive (NASA Exoplanet Science Institute, [70]).

## 2.1 Pulsar timing

The method of pulsar timing variations was used for the first discovery of the extrasolar planets orbiting the pulsar PSR B1257+12 (Wolszczan & Frail 1992 [119]). However, it is not a particularly successful method in consideration of the number of discovered planets. Up to this date, only seven extrasolar planets have been confirmed.

The method studies variations in the electromagnetic pulses coming from a pulsar. These pulses should be regular so that when the irregularities are detected it can be calculated whether they are caused by the mass of an exoplanet. Planets are causing the pulsars, like any other stars, to move around a gravitational center of the system. From the timing variations of pulses, several characteristics of the planets and their orbits can be calculated [119].

Extrasolar planets (and even the brown dwarfs) orbiting pulsars are incredibly interesting. A general idea is when the giant star collapses into a supernova explosion, its massive force destroys the whole planetary system. Therefore, since the first discoveries astronomers have been studying the ways how these planets were formed. Several possible scenarios were presented by Podsiadlowski in 1993 [82]. Ray and Loeb summarized in 2017 [84] the models of planetary formation and divide them into three categories. The first category presents the models of formation around an ordinary star before the supernova. It expects the exoplanets to survive this cataclysmic event. Another option is the planetary system is captured by the neutron star when it collides with a main sequence star. Both ways expect the planets to be created during a typical planetary formation as expected. The second category assumes formation after the supernova explosion. The third category of models presents planetary formation as the final stage in the evolution of binary systems of a millisecond pulsar and its stellar companion. These models expect the binary companion is evaporating and from the material which does not escape the system planets may be formed.

Apart from the formation and life cycle of an exoplanet orbiting a pulsar (and possibly surviving the supernova explosion), life on this planet is very unlikely due to the strong ambient radiation (Sinukoff et al. 2013 [91]).

[1] It is not a complete list. A more detailed summary can be found on Wikipedia pages: Methods of detecting exoplanets (retrieved on December 13, 2022, from `https://en.wikipedia.org/wiki/Methods_of_detecting_exoplanets` [115]).

## 2.2 Radial velocity measurements

One of the most successful methods of exoplanetary research is the method of radial velocity measurements or the Doppler method. Actually, the second highest number of exoplanet detections was made using this method, with many previously discovered exoplanet candidates being confirmed and characterized using RVs.

The RV method is an indirect method using the stellar spectra influenced by the presence of exoplanets (Bozza et al. 2016 [11]). The host star is influenced by the planet's mass, causing it to orbit around the star-planet barycentre. The movement is usually small in comparison to the planetary orbit, often the barycentre is located under the stellar surface. Radial velocities are determined from the Doppler shift of the spectra lines in the stellar spectra. Observed RVs are often in tens or small hundreds of kilometres per second (not strictly defined), depending on the various parameters, such as stellar and planetary mass, the semi-major axis of the planetary orbit (i.e. distance of the planet from the star), presence of other planets, etc. For example, the radial velocity of 51 Pegasi is approximately $100\,\mathrm{km\cdot s^{-1}}$ [61]. For the precise characterization of small planets or the study of their atmospheres the RVs lower than $10\,\mathrm{km\cdot s^{-1}}$ may be needed in particular cases. Several high-accuracy spectrographs were built with the purpose to gain required precision[2].

To determine the radial velocities from the Doppler shift it is necessary to compare the spectra to the RV template [11]. It can be a spectrum of the RV standard star. These stars have stable, not changing RVs. When choosing the RV standard for observations, it should be of the same spectral type as the studied star. This provides similar spectra and spectral lines in it which is optimal for comparison. The RV standards are chosen before the observation from several catalogues available[3]. A different method uses for the comparison the telluric lines appearing directly in the spectrum of the target star (Guenther & Wuchterl 2003 [35]). These spectral lines are the atmospheric features. They are caused by the molecules of water vapour in the Earth's atmosphere, which absorb and then emit their own light. This light contaminates the stellar spectra. However, the position of telluric lines is not changing in the spectrum. Thanks to this fact it can be used for the Doppler shift measurements (Dupkala 2019 [25]).

The most important parameter obtained from the method is the RV amplitude $K$. It is used to determine the nature of the object – whether it is a planet or a false positive (such as a binary system etc.). A high amplitude indicates a stellar nature of the object (or at least a brown dwarf) due to the great mass [35]. From the RV curve and its shape important parameters – orbital period $P$ and eccentricity $e$ – can be calculated. We need to know the mass of the host star $M_*$. Then we can express radial velocity amplitude $K$ as

[2]For example ESO spectrographs HARPS (High Accuracy Radial Velocity Planet Searcher) which was put in use in 2003 and ESPRESSO (Echelle Spectrograph for Rocky Exoplanet- and Stable Spectroscopic Observations) used since 2016.

[3]For example Geneva Radial Velocity Standard Stars (`http://obswww.unige.ch/~udry/std/std.html`).

$$K = \left(\frac{2\pi G}{P}\right)^{\frac{1}{3}} \frac{M_\mathrm{p} \sin i}{(M_\mathrm{p} + M_*)^{\frac{2}{3}}} \frac{1}{(1 - e^2)^{\frac{1}{2}}} \,, \tag{2.1}$$

where $M_\mathrm{p} \sin i$ is the mass of the exoplanet (Perryman 2000 [78]). The inclination $i$ cannot be obtained from the RV method alone, therefore follow-up observations are necessary. As mentioned before, the RV method and transit photometry make an excellent combination providing all the basic parameters for exoplanet characterization. Using only the RV method just the lower mass limit of the object can be derived. However, it may be enough to determine the false positivity.

Doppler analysis does not require the exoplanet to transit the parent star. However, it can provide additional information about the system if the transit occurs. Due to the stellar rotation, one quadrant of the stellar disk moves towards the observer, producing a blue shift in spectra. The other quadrant in opposition to this produces the red shift as it is moving away from the observer. As the exoplanet transits the star, it covers different parts of the stellar disk, resulting in slight changes in the RV. This effect is called the Rossiter-McLaughlin effect (Boué et al. 2013 [9]) and it is important for the calculation of various parameters, such as planet-star size ratio, speed of the stellar rotation, orbital inclination of the planet or other orbital parameters (the rotational spin directions of the exoplanets or the spin-orbit angle[4]. Last but not least, the RM effect can be used to determine the atmospheric composition or the detection of exo-moons[5] (natural exoplanet satellites as the Earth's Moon, Triaud 2018 [102]).

In addition to the radial velocities, there is much information about the star and its planetary system contained in the stellar spectra. RV method uses only the Doppler shift, but the location, intensity, and shape of the spectral lines provide information about the abundances of chemical elements, chemical composition, and the existence of the exo-atmosphere (Sing et al. 2016 [90]). Also, stellar spectroscopy is still used for the classification and characterization of the parent star necessary for the exoplanet characterization itself (Pepe et al. 2014 [77]).

For the spectral analysis of the stellar light, a spectrograph is necessary making the RV measurements more complicated than the photometric transit observations, which can be easily done even using smaller – amateur telescopes.

## 2.3 Transit photometry

A transit photometry is the most successful method of discovering extrasolar planets. Availability of the sufficient CCD cameras, which are used for stellar photometry, their compactness, and relative simplicity makes photometric observations an easy method of research both for ground based observatories and space telescopes. Even amateur astronomers can easily observe exoplanet transits of the bright stars with sufficient precision. The photometric observations can be scalable to large sky surveys when many stars are observed at once. This

[4] The angle between the stellar spin-axis and the orbit of the planet (shortly called the spin-orbit angle).

[5] As of now, there are several candidates for the exo-moon discovery, but none of them are exactly confirmed.

drastically increases the chances to detect a transit (as when more systems are observed, there is a higher chance one of them is in a good geometry for the transit detection).

Transit photometry studies the brightness of the host star. When the orbital plane of the exoplanet lies in the line of sight of a star from the Earth, the planet passes in front of the stellar disk. It creates a partial eclipse and a decrease in the stellar brightness is observed (i.e. a planetary transit occurs). The shape of the light curve can provide us with much information about the planet. From the time interval between two transits, we can determine the orbital period $P$ of the planet. According to Newton's gravitational law and Kepler's third law, we can calculate the semi-major axis $a$ of the planetary orbit (assuming the mass of the planet is far less than the mass of its host star $M_{\mathrm{p}} \ll M_*$) as

$$a^3 = \frac{GM_*}{4\pi} P^2 \,. \tag{2.2}$$

When the transit occurs the stellar brightness decreases. Assuming a uniform surface brightness of the parent star the luminosity drop can be approximated to

$$\frac{\Delta L}{L_*} \simeq \left(\frac{R_{\mathrm{p}}}{R_*}\right)^2 = \delta \,, \tag{2.3}$$

where $\Delta L$ stands for the drop in luminosity, $L_*$ represents luminosity of the host star and $R_{\mathrm{p}}$ ($R_*$) is the radius of the planet (star). The symbol $\delta$ stands for the transit depth (Perryman 2000 [78]). For a higher precision we need to consider the effect of limb darkening[6] in our calculations (Jacob et al. 2000 [43]). Thanks to the formula (2.3) for the luminosity drop we can derive a planet-to-star radius. If the stellar parameters are known the planet's radius can be determined.

We can calculate the transit duration as well, as

$$\tau = \frac{P}{\pi} \left( \frac{R_* \cos d + R_{\mathrm{p}}}{a} \right) \,, \tag{2.4}$$

where $d$ stands for the transit latitude on the stellar disk [78]. It can be derived directly from the equation (2.4) since we know the transit duration directly from the light curve.

Finally we can derive one of the most important parameters – the orbital inclination $i$ as

$$\cos i = \frac{R_* \sin d}{a} \,. \tag{2.5}$$

As mentioned before, a disadvantage is that not all the planets orbit their parent star under the right angle, so just a fraction of exoplanets can be studied using this method. On the other side, most of the space telescopes conducting wide-angle stellar surveys use transit photometry for its simplicity and efficiency. With the TESS mission currently operating and the PLATO mission planned in the near future, most of the exoplanets will continue to be discovered via the method.

[6] "Decrease in the brightness can be observed on the edge of the stellar disk due to light passing through the thicker stellar atmosphere." (Dupkala 2019 [25])

## 2.4 Direct imaging

The first indications of direct imaging of the exoplanet were images made by the Hubble Space Telescope showing a planet-like candidate orbiting Fomalhaut (as described above in sub-chapter 1.3). Direct imaging in visible light wavelengths is difficult, as the stars usually have a brightness billion times higher than the planets orbiting them[7] (their reflection of the stellar light respectively, [11]). Another problem is the small angle distance of exoplanets from their host star. A useful simile to get the image of the difficulties is to try to observe by the naked eye a firefly flying around the street lamp from a ten kilometres distance.

Of course, the brightness ratio depends on various parameters, most importantly the brightness of the star, planetary albedo, its radius, distance from the parent star, etc. The exoplanets orbiting further away from their parent stars reflect minimum starlight. On the other hand, close-orbiting planets may be difficult to observe.

Even through the difficulties, direct imaging is possible in the case of many exoplanets located close to the Earth. The imaging is much easier in the infrared part of the spectrum, as the brightness difference is much smaller (yet, it is still significant). To help with the direct view of one or even more exoplanets, coronagraphs are used to block the light from the star. Especially the bigger exoplanets orbiting further away from the star may have a thermal emission large enough for detection.

There are currently more than 60 exoplanets discovered using the method of direct imaging. The exact techniques used for imaging vary as the possibilities may be limited depending on various parameters of the stellar system (as mentioned above). The first exoplanet discovered by direct imagining – in the infrared part of the spectrum – was 2M1207b (Figure 2.1) discovered by the Very Large Telescope (VLT) at the Paranal Observatory in Chile (Chauvin et al. 2004 [19], Mohanty et al. 2007 [66]). The planet is a gas giant orbiting a brown dwarf (full designation 2MASS1207-3932), which is an undeveloped star. Thanks to this fact the brown dwarf is only around 100 times brighter than the planet providing an ideal possibility for imaging.

In 2008 using the Keck and Gemini telescopes at the Hawaiian observatories the first multi-planetary system HR 8799 (Figure 2.2) was discovered via direct imaging. Thanks to the adaptive optics and the observations in the infrared part of the spectrum three planets were discovered (Marois et al. 2008 [62]). Later observations detected the fourth exoplanet in the system (Marois et al. 2010 [63]). All the planets are gas giants. Three of them orbit the parent star with the semi-major axis between 16 to 42 AU. The fourth planet orbits almost 72 AU away from the star, inside of the dusty disk. There may be other (possibly terrestrial) planets located in the inner parts of the system. We observe the orbital plane of the system from the top view. Thanks to long-term observations astronomers are now able to show a beautiful video of planets orbiting their parent star HR 8799[8].

Quite famous are images of the exoplanet $\beta$ Pictoris b (Figure 2.3). It is

[7]This is the case for the Jupiter orbiting our Sun. All other planets in the Solar system are even fainter compared to the Sun.

[8]The video can be found for example on the Wikipedia pages: HR 8799 (retrieved on December 13, 2022, from `https://en.wikipedia.org/wiki/HR_8799`).

orbiting a young A-type main sequence star which has a system of two planets and debris disks. The existence of the disks is known since 1984 thanks to the unusually strong infrared radiation (for a star of this type). It is a young system close to the Sun (circa 63 ly) which made it a good target for possible direct detection of exoplanets. The first one – $\beta$ Pictoris b was discovered via this method in 2008 (Lagrange et al. 2009 [53]). The second planet, $\beta$ Pictoris c was discovered indirectly using the RV method through the long-therm observations with the HARPS spectroscope (Lagrange et al. 2019 [54]). Both planets are gas giants.

Direct observation of the exoplanets provides as with a lot of information, especially thanks to the detected clear exoplanet spectra. Also, the result of direct imaging is a real picture of existing exoplanet giving us not only the substantial proof, but the excellent material for the outreach as well.

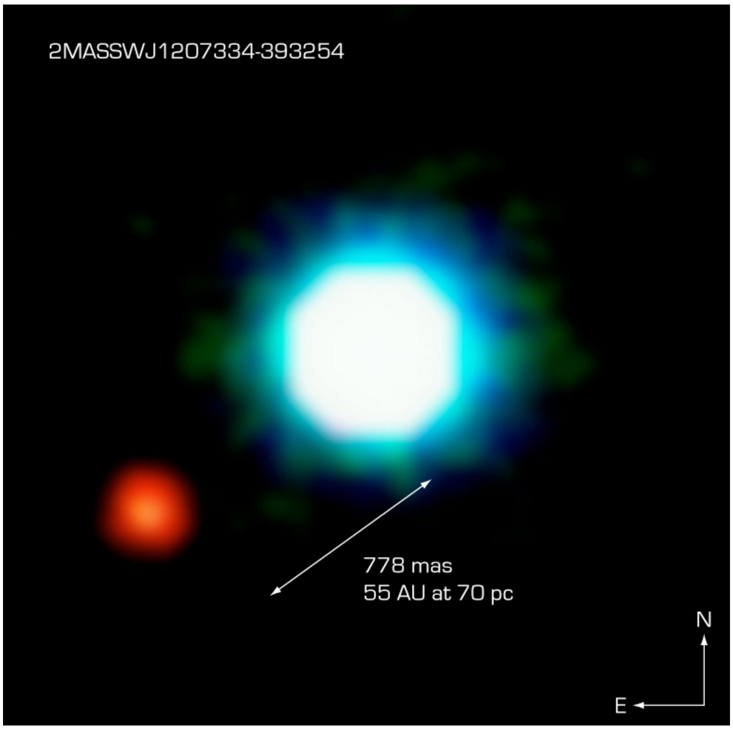


Figure 2.1: Image of the first exoplanet to be discovered via direct imaging. The discovery was made using ESO VLT. Image taken from Chauvin et al. 2004 [19].

## 2.5 Other methods

### 2.5.1 Pulsation timing variations

Similar to the pulsar timing, pulsations of some types of variable stars are used to detect the exoplanets. Only two planets discovered using pulsation timing are confirmed up to this date (Silvotti et al. 2007 [89] and Murphy et al. 2016 [69]).

### 2.5.2 Transit timing and transit duration variation

Both methods study the slight variations in the periodicity of the exoplanet transit and its length. From these irregularities, the presence of additional planets may be calculated [115]. While the transit timing cannot provide us with much information about the planets themselves, it is useful for studying distant systems, for which the radial velocities are not obtainable with the signal-to-noise ratio (SNR) high enough. On the contrary, the transit duration variations could be the source of some information. It may be a viable method for discovering the exo-moons. More than 20 exoplanets were found using these methods.

### 2.5.3 Gravitational microlensing

The phenomenon of gravitational microlensing occurs when two stars overlap from the observer's point of view (they need to be aligned almost perfectly). The gravitational field of the front star shapes light from the star behind, acting like the optical lens. when the planet is orbiting the front star its additional weight can be detected [115]. The gravitational microlensing can last for a few days or weeks. However, it will not repeat, as the alignment has a very small chance to happen. That gives just one chance to study the effect when occurring. To detect microlensing it is necessary to monitor many stars. This method works best for the stars located between the Earth and the center of our Galaxy, thanks to all the stars in the background. To this day almost 150 exoplanets have been found using this method.

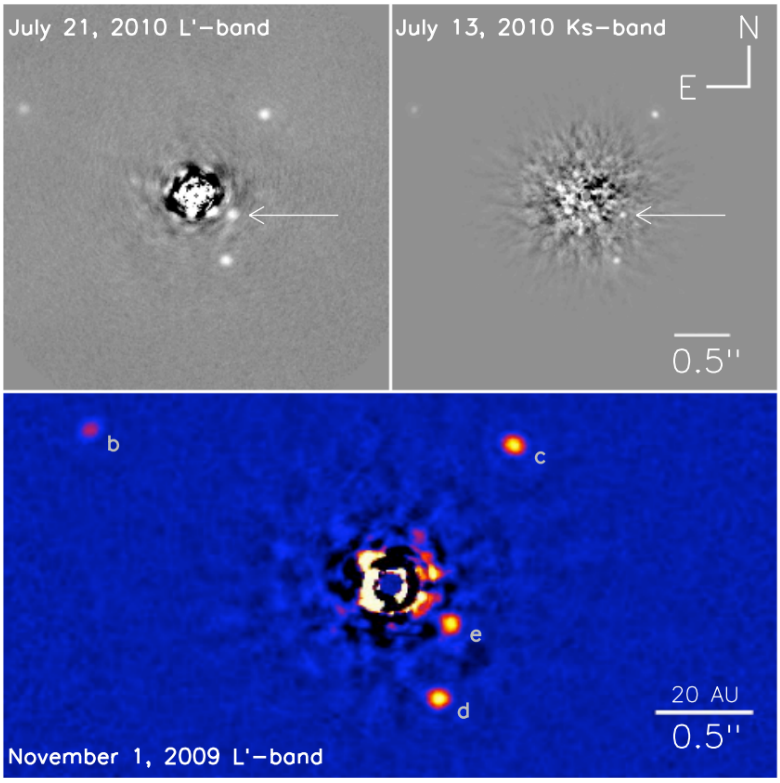


Figure 2.2: Direct images of the HR 8799 planetary system. Image taken from Marois et al. 2010 [63].

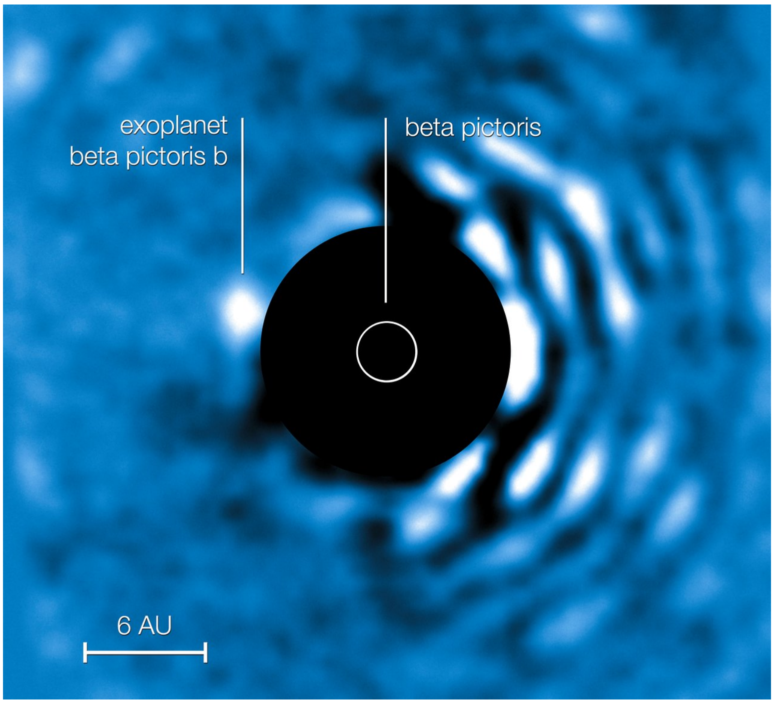


Figure 2.3: Direct image of the exoplanet $\beta$ Pictoris b taken with VLT's NACO instrument using the Apodising Phase Plate (APP) coronagraph. Image credits to ESA.

# 3. Research in the Czech Republic

The research of exoplanets began in the Czech Republic like anywhere else in the world. After the first discoveries and continuing development of observational techniques and research methods, it has found its place in Czech astronomical research as well.

Thanks to international collaborations and a large number of various opportunities in the last decades many Czech astronomers study and work at foreign universities and research institutions. A key element for the research and collaboration development is a membership of the Czech Republic in two major international institutions – ESO (European Organisation for Astronomical Research in the Southern Hemisphere) and ESA (European Space Agency). Both institutions were built on the bases of cooperation between European countries. The Czech Republic became a member of ESO in 2007 and a member of ESA a year later in 2008.

Membership in ESO gives Czech astronomers a voice in the decision-making process and the selection of the research projects conducted by ESO. It brings better collaboration and access to observational time, both being necessary for more in-depth research (not only the exoplanet research).

In the Czech Republic, the research activities in the field of exoplanetary science can be divided into three groups. The first group consists of the actual observations and data gathering. As there are only two telescopes with a diameter larger than one meter[1] and just a few telescopes in the diameter range of 0.5 – 1 meter, the observational possibilities in the Czech Republic are rather limited. This applies especially to precise radial velocity measurements. However, as mentioned before, transit photometry does not require large telescopes or any special apparatus. Therefore, photometric observations of sufficient quality are possible.

The second group represents research based on the data acquired with the use of space telescopes, large-scale sky surveys, or other ground based observatories. The third group represents the involvement in space missions, which became notable mainly thanks to the PLATO mission and the Czech participation in it.

## 3.1 Transit photometry and ETD

A huge contribution to the exoplanetary research was done by astronomers conducting the transit observations, gathering a lot of data through the Exoplanet Transit Database[2] (ETD). It is operated by the Variable Star and Exoplanet Section of the Czech Astronomical Society. The society is a voluntary association that unites both professional and amateur astronomers in the Czech Republic. It

[1]Larger than 1 m are only the Perek Telescope at the Ondřejov observatory (with 2 m diameter), and telescope KLENOT (diameter of 1.06 m) at the Kleť observatory. Retrieved on December 31, 2022, from Wikipedia: Největší dalekohledy v Česku https://cs.wikipedia.org/wiki/Nejv%C4%9Bt%C5%A1%C3%AD_dalekohledy_v_%C4%8Cesku.

[2]Accessible at http://var2.astro.cz/ETD.

was founded in 1917, with the Variable Star and Exoplanet Section founded in 1924. For the majority of the time, the main subject of the study was variable stars, a topic quite popular in the region. Recently, with the wide spread of exoplanetary research, it became one of the objects of interest, thanks to its similarity to the research of variable stars. A special project dedicated to the research of exoplanets has formed under the Variable Star and Exoplanet Section called TRESCA[3] (TRansiting ExoplanetS and CAndidates). As the name implies the project is aimed at transit photometry. Astronomers working on TRESCA observe planetary systems already known and look for possible new exoplanets there. They search for new systems as well.

The first photometric observation[4] of the exoplanetary transit in the Czech Republic was done at the Brno Observatory and Planetarium in September 2004 (Czech Astronomical Society 2004 [23]). The 0.4 m telescope equipped with CCD camera ST-7 was used by Ondřej Pejcha, back then the Charles University student and co-worker at the observatory. He detected the transit of exoplanet TrES-1b discovered just a few weeks before. The planet is the hot Jupiter orbiting an orange dwarf star.

Since then many astronomers have participated in transit observations. In September 2008 the ETD came online (Poddaný et al. 2010 [81]) gathering data and providing useful information for observers. The database gives the transit predictions for every night. It is also used for uploading and processing the photometric data from the observed transits, the data are fitted directly after inserting into the database. From the results, the database plots the observed – computed diagrams providing results, such as the central time of transit, its duration, and depth.

As mentioned in chapter 2, a combination of transit photometry and Doppler spectroscopy is important for the full characterization of exoplanets and their advanced research (e.g. for RM effect detection). This fact emphasizes the significance of ETD and the transit observations carried out by many astronomers in the Czech Republic.

## 3.2 RV measurements with the Perek telescope

The first research group specially dedicated to the study of exoplanets was created at the Astronomical Institute of the Czech Academy of Sciences (AI CAS) under Dr. Petr Kabáth. Since 2015 the main dedication has been radial velocity follow-up observations of exoplanetary candidates and characterization of the exoplanetary atmospheres (Kabáth et al. 2020 [45]).

The exoplanet group uses 2-meter Perek[5] telescope at the Ondřejov observatory of AI CAS, operated by the Stellar department (Figure 3.1). The telescope was built in 1967[6] and it still holds the title of the largest telescope in the Czech

[3]The web pages of the TRESCA project are accessible at `http://var2.astro.cz/tresca/?lang=en`

[4]At least according to the available sources [23]. There may have been previous unannounced detections.

[5]The telescope was constructed thanks to the initiative of Luboš Perek, a Czech astronomer, whose name it bears since 2012.

[6]When the telescope was built, it was the 9th biggest telescope in the world.

Republic. It is a coudé system on a special equatorial mount (Šlechta & Škoda 2002 [93]). The telescope is mostly used for stellar spectroscopy. It is equipped with an echelle spectrograph OES (Ondřejov Echelle Spectrograph, Koubský et al. 2004 [52]) with a CCD camera and a single order coudé spectrograph working in two configurations (with CD400 and CD700 camera [93]).

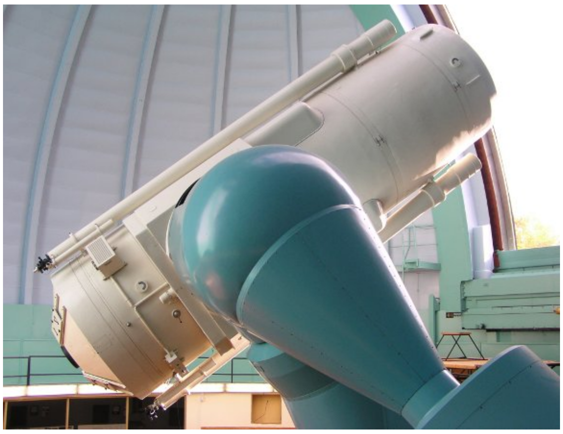

Figure 3.1: Perek 2-meter telescope at Ondřejov observatory. Picture taken from the web pages of the Stellar department of AI CAS [94].

The main optical element of the telescope is a parabolical mirror with an effective diameter of 2 meters. Its focal length is 9 meters with a focal ratio 1:4.5 [93]. After the reconstruction finished in 2020, a complicated optical system of mirrors was replaced with the optical cables leading from the focal point of the primary mirror straight to the spectrographs (Šlechta 2020 [92]). With this modernization, a CCD camera for the photometric observations was installed in the focal point as well. A new control room was created in the basement of the office building which is located next to the telescope dome. The telescope is usually operated by two people – a technician (responsible for running and maintenance of the telescope) and an astronomer leading the night observation program. Astronomers can access the telescope remotely as well, which proved helpful especially during the COVID-19 pandemic.

The OES spectrograph is used for obtaining all the spectra for the exoplanet research. It creates many narrow orders which are overlapping (in comparison to the single order spectrograph which works only in two spectral orders). Thanks to this fact, it is possible to merge them into one continuous spectrum covering a large wavelength range (Dupkala 2019 [25]). This might cover even more than just the visible light spectrum, even though for data processing this range does not need to be used all the time in full width.

In the beginning, the main focus was the follow-up observations of Kepler candidates. However, as mentioned in sub-chapter 1.3, most of these candidates were difficult to observe using meter-sized telescopes as the stars were too faint to get the RV measurements of sufficient precision. Mission TESS is more suitable for the follow-up observations (Kabáth et al. 2019 [46]) and TESS candidates are now the main targets of the research. The follow-up observations will continue as well for the candidates discovered by the PLATO mission. Czech involvement in the mission, which resulted in joining its consortium in 2019, is coordinated by Dr. Kabáth (see below).

The exoplanet group is involved in several international collaborations such as the PLATOSpec project (see below) or the KESPRINT consortium. The latter one is dedicated to the detection and characterization of transiting exoplanets discovered by space missions (KESPRINT web pages [48]). Astronomers joined in KESPRINT combine several research methods (photometry of transits, RV measurements, spectral analysis) and complete them with theoretical interpretations in order to get a detailed understanding of studied exoplanetary systems (Kabáth et al. 2022 [44]). Thanks to the KESPRINT and the exoplanets group at AI CAS TOI-503b – the first transiting brown dwarf discovered by the TESS mission – was characterized (Šubjak et al. 2020 [97]).

## 3.3 PLATOSpec

The project PLATOSpec was created in 2017 as the joint effort of the exoplanet groups of AI CAS and Thüringer Landessternwarte Tautenburg (Karl Schwarzschild Observatory)[7]. The idea was to find an unused telescope of small meter-sized class (between 1 and 2 metres in diameter) for the follow-up observations of exoplanet candidates discovered by the TESS and PLATO missions (PLATOSpec web pages [80]). A former ESO telescope at La Silla, Chile with 1.52 m diameter was chosen, as it was not in service since 2003. After the ESO Scientific Technical Committee approval and funding approval by the Czech Academy of Sciences, a refurbishment of the telescope began in 2020.

The project got its name after the new spectrograph PLATOSpec, which will be installed at the observatory for precise RV measurements and spectral analysis. The expected precision is around $3\,\mathrm{m s^{-1}}$ [80]. The spectrograph is being constructed at the Pontificia Universidad Católica de Chile, which contributes to the project as well and will help with the spectrograph's maintenance. It is expected the PLATOSpec spectrograph will be operational in 2023. Until then a similar spectrograph PUCHEROS is being used for observations (Suchan 2020 [98]).

## 3.4 PLATO mission

As written before, in 2019 the Czech Republic became a member of the PLATO consortium. The Czech participation in the mission is supported by the Ministry of Education, Youth and Sports with the amount of 840,000 euros from the money allocated in the ESA PRODEX program (Trtíková, May 2019 [103]). The Czech Republic will contribute to the mission by delivering the transport containers for PLATO's 26 cameras. In sum, 33 containers will be constructed. It is crucial for the containers to keep the PLATO's cameras safe. These high-tech containers are currently under construction by the Czech firm S.A.B. Aerospace s.r.o.

For Czech researchers, participation in the mission will bring exclusive access to the data obtained by PLATO. They will take part in the data analysis. The Czech group will also be a part of the PLATO PCOT (PLATO Calibration and

[7]Both groups are using the 2-meter twin telescopes of ZEISS production, the largest telescopes located in the Czech Republic and Germany respectively.

Operations Team) which will develop software for the data processing and evaluation and monitoring of the instruments in the preparatory phase of the mission [103]. As a member of the consortium the Czech Republic will be able to join the decision-making process and thus will get the opportunity to participate in the success of the mission.

Participation in the mission will help with the effort of follow-up observations. Thanks to the experience gained with the TESS mission and the network of observatories (e.g. Ondřejov, Tautenburg, and PLATOSpec) built during the process, the Czech astronomers will be at the forefront of the exoplanet research initiated by the PLATO findings.

## 3.5 ARIEL mission

Another ESA mission with the participation of the Czech Republic is ARIEL (Atmospheric Remote-sensing Infrared Exoplanet Large-survey). It is a space telescope dedicated to exoplanet research (Wikipedia: ARIEL [108]). Unlike PLATO, ARIEL will observe only one target at a time. It will observe the exoplanetary transits in the infrared part of the spectrum. ARIEL aims to study exo-atmospheres, their chemical composition, and their thermal structures. The objective of the mission is to gather data on at least a thousand exoplanets and answer questions on their formation and evolution. ARIEL is expected to launch in 2029 [108] and it will travel to the Lagrange L2 point where it will find its stable position for the observations.

Same to the PLATO mission, the Czech participation in ARIEL is supported by the Ministry of Education, Youth and Sports with the amount of 1.65 million euros from the money allocated in the ESA PRODEX program (Trtíková, Nov 2019 [104]). The Czech components will be made by the research center TOPTEC under the Institute of Plasma Physics of the Czech Academy of Sciences. They will build the optical components – secondary mirrors for the spacecraft, which will guide the light from the primary elliptical mirror to the spectral instruments (Žďárská 2021 [120]).

Participation in the mission will also bring access to the obtained data and much-valued opportunity to shape the decisions about the mission as a member of its consortium. Coordinators of the Czech engagement are Dr. Martin Ferus and prof. Svatopluk Civiš, both from the J. Heyrovský Institute of Physical Chemistry of the Czech Academy of Sciences.

# 4. Summary of the outreach activities

Since the beginning of time, mankind has looked up to stars. They have found there amazement, the muse, mythical stories or even the source of knowledge. Humans have learned to use the sky as a calendar[1], what was indispensable for farming, protection against the natural elements and the overall evolution of society.

The night sky is a nature's wonder and humans have always dreamed about travelling to the seemingly unreachable stars. This has proved in the second half of the 20th century during the space race. Human space missions quickly became global events. When the Apollo 11 mission successfully landed on the Moon 650 million people[2] were watching it live on the TV. Several space probes travelled to the distant planets of the Solar system and a few of them successfully landed on Mars and Venus. These missions showed us amazing images – colourful and sharp photos of different worlds.

People have had many thoughts about their place in the universe and the possibilities of extraterrestrial life. As the Voyager missions headed out of the Solar system, they carried a special plate with information about mankind, should they ever reach other civilizations. With the Hubble Space Telescope, humans could see deep into the universe. The famous image of the Hubble Deep Field[3] made astronomers realise that the dark and empty void is actually full of distant galaxies.

Thanks to all of this, astronomy has always had a special place among the science disciplines. Even though the real physics behind it may appear difficult and the math formulas and models may be unimaginable for many people, it is possible to present it in a simple, attractive way. Excitement for space exploration highlights it even more. The research on exoplanets fits perfectly into this narrative. It is a new and exciting field which has a lot to offer. A general enthusiasm for the subject only proves it.

## 4.1 General approach to the outreach

As described above, the interest in the research of exoplanets is high and it has strong philosophical, historical and cultural bases. It is easy to get excited about the subject, no matter the audience – astronomy enthusiasts, children and students or the general public.

[1]A well-known example is the megaliths – the stone structures from the Neolithic period. Some of them were used as calendars, Stonehenge for instance. There is one located in Warren Field, Scotland, which is also the oldest calendar, built as a stone monument in the Mesolithic period approx. 8,000 BCE (Gaffney et al. 2013 [29]).

[2]Data retrieved on December 18, 2022, from NASA web pages `https://www.nasa.gov/mission_pages/apollo/missions/apollo11.html`.

[3]The image assembled from 342 separated shots in the constellation Ursa Major was taken in December 1995. Later, other images were taken – Hubble Ultra-Deep Field and Hubble eXtreme Deep Field allowed us to look even deeper into the universe.

In the introduction of this thesis, we described several reasons why the outreach of this topic is important – the search for the new Earth or a possible extraterrestrial life, information about the evolution of our planetary system as well as the pragmatic reasons like getting the support and funding for the research. Here we are presenting several possible approaches to the outreach. In reality, many news, reports and activities combine these approaches, as they are closely connected and easy to combine. This achieves an even greater effect in promoting the field.

### 4.1.1 Extraterrestrial life and the new Earth

The biggest attraction the research of exoplanets has to offer is the search for an answer to the big question – "Are we alone in the universe?" In the 21st century, it is still an open question. Recently increased interest in it, which is notable especially since the last century, was following the boom of the science-fiction genre in pop culture, the popularity of UFO stories and the development of science and technology.

The term "UFO", meaning unidentified flying object, has appeared since World War II with the rise of military aviation. At first soldiers and aviators reported the strange light effects, later the civilians witnessed similar phenomena. It was often associated with inexplicable movement patterns, quickly disappearing. Most of the observations were later explained through the military tests of the new equipment or the various meteorological phenomena[4]. Nevertheless, it raised the question of extraterrestrial life. Sci-fi movies and books followed up this trend, especially those with a space theme. Most of them offered breathtaking images of the universe, distant worlds, spaceship battles or interstellar civilizations. They impressed a large audience.

The exoplanetary research appeals to all of these popular topics as the new findings are presenting information directly connected to them. It shifts sci-fi more to the field of real science. The ideas of life in the universe, travelling to other planets and searching for the new Earth are becoming a serious scientific debate, without losing anything from its simplicity and attractiveness. On contrary, the presented discoveries of new exoplanets with strange characteristics never seen before are always received with high interest. The media like to present these discoveries as well (often as a refreshing part of the news coverage).

Quite popular are the discoveries of atypical exoplanets or the planetary system, such as the "Tatooine-like systems", where the exoplanet orbits multiple-star systems. In the Star Wars movie franchise, Tatooine is a desert planet in a binary system. In the iconic scene, Luke Skywalker watches a double sunset over the sand dunes (see Figure 4.1). The first planet of this kind (even though not the habitable one), Kepler-16b, was discovered in 2011 by Kepler Space Telescope (Choi 2011 [20]). Discoveries like this one are often promoted with an image of the artist's imagination of the system. There are many various pictures of this kind widely shared by the media. It helps people to imagine what could the systems look like, making the subject more understandable and accessible.

[4] For example the upper-atmospheric lightning – various phenomena as the blue jets, red sprites of Elves or Trolls (Wikipedia: Upper-atmospheric lighting, retrieved on December 19, 2022, from `https://en.wikipedia.org/wiki/Upper-atmospheric_lightning`).

Figure 4.1: In the left picture, there is the iconic movie scene of the double sunset on Tatooine from Star Wars: Episode IV – A New Hope (1977). In the right picture, there is an artist's imagination of the Kepler-16 system. Image credits to Disney/Lucasfilm (left) and NASA/JPL-Caltech (right).

Like Star Wars movies and the TV series, the space sci-fi genre often presents new worlds – travelling from planet to planet with various exotic characteristics and life forms (Star Trek, Marvel's Guardians of the Galaxy, Avatar, Dune or a cartoon series Futurama etc.). These motives are highly popular, as they feed the human imagination of how the distant worlds could look like. That appeals to a human will to explore the unknown. In a way, it reminds the travel documents even though most of it is just fiction – so far. However, there have been several movies or books working with the facts already known about exoplanets. A good example is the Avatar movie from 2009 (directed by James Cameron). The movie plot is set on the exo-moon called Pandora, which orbits a gas giant planet. This is based on the fact that, unlike their host exo-planets, some exo-moons may be habitable.

In conclusion, one of the outreach methods is to connect the message (a TV shot, lecture, an article on the web pages or social media etc.) with a reference to life in the universe or a search for the second Earth. It helps to grasp the purpose of the research and therefore it helps to better understand the content of the message in a broader context.

### 4.1.2 Cosmonautics and the space missions

Another way how to approach exoplanet popularization is through space missions. As stated before, cosmonautics has always attracted people. The new methods of studying exoplanets using space telescopes open new options.

Rocket launches, space missions and exploration, are extremely popular since their beginnings. A high level of engineering and innovative process is needed to succeed. The missions usually come with a high risk of failure. People are excited to watch the live coverage, commentaries are made with images showing the atmosphere in the control centre etc. The attractiveness and general excitement help to promote the research in the standard or so-called mainstream media, which dedicate only a small portion of their coverage to scientific topics.

It is not only about the piloted mission to space. The space probes landing on Mars (e.g. NASA Opportunity or Curiosity missions) or the Hubble Space Telescope became famous through the discoveries they have made and the stunning images they have sent back to Earth. So far the most famous exoplanet mission is the Kepler Space Telescope. Especially during 2013 and 2014 (and later with new data packages presented), several discoveries made headlines, announcing detections of hundreds of exoplanet candidates (e.g. NASA 2013 [71] or CNN/Strickland 2017 [95]).

Nowadays space missions play a key role in exoplanet research. Alongside the new discoveries they have made, their direct connection to cosmonautics makes them a valuable part of the exoplanetary outreach. The involvement of the local Czech companies in the PLATO and ARIEL mission preparations only multiplies the impact on the Czech audience.

### 4.1.3 New discoveries

Presenting new discoveries and findings has always been a shiny part of scientific research. Knowledge and education have been the driving wheel of the human evolution and development of society. As of today, new and fascinating discoveries made headlines all over the world. Exoplanetary research as a relatively new field of astronomy has a lot to offer. There are large areas unknown to astronomers. New information is discovered on weekly bases. Thanks to the variability of detected planets, each announcement presents some new information or data, helping the exoplanet outreach.

Especially the notable “firsts” are popular, such as the first exoplanet discovered, the first exoplanet transit detection or the first exoplanet detected by Kepler or TESS. Once again, the exoplanets have a lot to offer, as many more milestones are yet to be uncovered (e.g. the first Earth-like exoplanet with the confirmed detection of liquid water on the surface etc.). The discovery of 51 Pegasi b was a huge success and it quickly became famous not only in the astronomical community (Grygar 1996 [34]).

The records and rankings are highly popular, similar to sports statistics. There are many rankings of exoplanets according to the size, orbital period, distance from the Earth etc[5]. NASA created Kepler’s Hall of Fame[6] listing small habitable zone exoplanets discovered by the telescope. These planets are believed to have the best parameters suited for life from the exoplanets already known (the list as of January 2015).

## 4.2 The media

A choice of platform for outreach is important. However, thanks to the nature of the subject of exoplanets and its general popularity, it is hard to choose badly. Research findings are often easily supplemented by artistic images (as seen in Figure 4.1) or animations. This allows addition of a graphic element to the

[5]Many rankings and lists of exoplanets can be found on the Wikipedia web pages accessible from the main page [111].

[6]Information from the list updated in January 2015, retrieved on December 21, 2022, available at `https://exoplanets.nasa.gov/resources/243/nasa-keplers-hall-of-fame-small-habitable-zone-exoplanets/`.)

presented message, increasing its media outreach in visually-oriented media, such as television or some magazines.

Currently, the leading platform for the fast sharing of information is social media. They are visually oriented as well and they provide a great place for exoplanetary outreach. For an article or a post to have a better reach, it needs to have an exciting, almost tempting title or image, which makes people curious about it. In a mostly negative connotation connected with lies and deception, it is called clickbait. However, for the news on exoplanets, it is quite easy to create an interesting title without any deception of readers.

As an example may serve a web portal `space.com` (more information below). This summer, an article was published with the title "Possible water world spotted orbiting an alien star" [21]. It informs about the discovery of an ocean planet in a habitable zone by the TESS mission. Another title "James Webb Space Telescope reveals alien planet's atmosphere like never before" [83] captions the article about the newest observation of the James Webb Space Telescope. Just recently there was published an article about the discovery of two potentially habitable planets in close proximity to the Solar System under the title "Two potentially habitable Earth-like worlds orbit a star in our cosmic backyard" [57]. In two out of three presented titles the word "alien" is used as it is more noticeable than for example, "extrasolar". In one title the word "backyard" induces the connection with our home. Author uses this word instead of "close to the Sun" or "in close proximity", since both have a less emotional connotation. Therefore, it increases the chances people will engage and read the article and yet it is not a deception, as the title is stating the true fact described in detail in the article.

Science outreach is rapidly expanding on social media. For example, the Twitter account of NASA has more than 68 million followers, with a special account created just for information on exoplanet research – NASA Exoplanets with 1.3 million followers[7]. Therefore, a proper accent should be given to the exoplanetary outreach on social media as well.

## 4.3 Outreach forms and activities

Following the conclusion of the previous sub-chapters, most of the coverage of the exoplanet outreach is done via television or online reporting – web articles, posts on social media, TV news etc. All of these can offer both short messages or more detailed formats. In the TV, scientific debates or interviews[8] bring interesting new findings or explain the basic research to the public. Various documents and videos present the research in a more visual form. Recordings are often posted online on social media, especially YouTube (an online video platform). In recent years podcasts partially took the function of the TV bringing many interviews with scientists, popular lectures or the more-in-depth analyses.

In-person activities are as important as media coverage. They offer a stronger and often more personalized experience. The most common example is popular and educational lectures. They can have many forms, depending on the audience

[7] The numbers are from December 20, 2022. Accounts are accessible at `https://twitter.com/NASA` and `https://twitter.com/NASAExoplanets`.

[8] Popular TV program Hyde Park Civilizace with Dr. Petr Kabáth available at `https://www.ceskatelevize.cz/porady/10441294653-hyde-park-civilizace/222411058091029/`.

(e.g. for children, students or the general public), environment (at the university, observatory or in the planetarium etc.), the format of presentation and the exact topic (research methods and basic overview or the habitable zones and search for extraterrestrial life).

Another approach is via night sky observations. There are many observatories open to the public in the Czech Republic. When the weather conditions allow it a few hours long observation (depending on the capacity and possibilities of the observatory) may tickle the subject of exoplanets. Mostly, exoplanets are not a good target for public observations, as it is not possible to show more than "just a star". However, it gives the time to talk about exoplanetary research, which is usually a grateful subject of discussion. Variations of this, independent of time or weather conditions, are offered by the planetariums. Thanks to modern machinery it is possible to enrich the sky tour with pictures and animations useful for better presentation and understanding. Modern planetariums present a wide scale of programs – many of them focused on exoplanets – with high educational and artistic value.

Quite popular in recent years are the interactive science centres. There are around 10 science centres in the Czech Republic and several of them have exhibitions at least partially connected to astronomy. These centres are visited by both school trips and the public (often families with children), therefore providing a unique opportunity for the outreach of the exoplanets.

Seminars and workshops are organized combining the lectures and more hands-on experiences, often with the objective to teach students or fellow astronomers methods of observation and data processing or to share scientific news with the community. In 2018, the Czech Republic celebrated 10 years in ESA. As part of the celebration, a scientific workshop for students and young researchers was held in Prague with an appropriate name "10 Years of the Czech Republic in ESA"[9]. As part of the workshop, a conference took place, where the successes of the Czech membership in ESA were presented, connecting research institutions and aerospace companies. It was attended by the members of parliament and the government of the Czech Republic as well as the director general of ESA. The event had no special focus, but the subject of exoplanetary research, especially with several missions planned by ESA, was included as well.

Special events, such as open-door days at research institutions, are other great occasions for outreach. As it is their primary objective, people attending these events are expecting some level of educational activities, which helps the understanding of the topic. This applies to most of the activities mentioned above.

### 4.3.1 NameExoWorlds campaign

An interesting campaign was launched by the International Astronomical Union (IAU) in 2015. It was called NameExoWorlds[10] with the simple objective – to give the general public an opportunity to name several of the discovered exoplanets. A variety of astronomical organizations from 45 different countries could submit their suggested names. Then the public decided in the vote on the names for 19 exo-worlds (14 stars and 31 exoplanets orbiting them). Over half a

[9] `http://workshop.vesmirprolidstvo.cz/`

[10] Web pages accessible at `nameexoworlds.iau.org` [42].

million votes were submitted from 182 different countries around the world (Pasachoff & Filippenko 2019 [75]). The chosen names can be used freely alongside the catalogue designations (see sub-chapter 1.2.1). As the result, for example, the star 51 Pegasi hosting famous exoplanet 51 Pegasi b was named Helvetios, with the planed named Dimidium.

The second campaign was organized in 2019 for the hundredth anniversary of the IAU. Every member state was assigned a star with the exoplanet to name, again the public vote decided the final names. The Czech Republic was appointed to name the star XO-5 with the exoplanet XO-5 b, in the constellation Lynx. The elected name of the star is Absolutno, with its exoplanet named Makropulos. Both names are inspired by the work of Czech writer Karel Čapek, a pioneer of the science-fiction genre [42].

The third campaign has been launched in 2022 with the deadline for name submissions on December 11. The results have not been published yet.

As an interesting fact, some people were not happy with the new names, as several exoplanets were given unofficial names before by astronomy enthusiasts. These names were not respected in the NameExoWorlds campaign. For example, 51 Pegasi b (now called Dimidium) was unofficially known as Bellerophon. This name was abandoned after the first NameExoWorlds campaign.

### 4.3.2 The Nobel Prize in Physics 2019

The announcement of the Nobel Prize in Physics awarded for the research on exoplanets was a major event. It was awarded to Michel Mayor and Didier Queloz for discovering planet 51 Pegasi b, alongside James Peebles for theoretical discoveries in physical cosmology. The Nobel Prize announcements always draw the attention of the world media, which try to explain the awarded research to the public. Each year, there are numerous television debates with scientists, public lectures etc.

Following the announcement in 2019, the media coverage of the topic was strong in the Czech Republic as well, offering many articles[11,12] or reportage in the evening news. Several Nobel lectures were organized in order to explain the science topics which were awarded by the Nobel Committee.

## 4.4 Activities conducted by the author

During the course of writing this thesis and even before, numerous outreach activities were conducted by the author.

The night sky observations for the public were some of the first activities done before the work on this thesis has begun. They were conducted mostly at the Observatory of Kysucké Nové Mesto under the Regional Observatory in Žilina, Slovakia. As described in section 4.3, the observations were conceived as the surveys of objects visible in the night sky – from the Moon and visible planets of the Solar system, through the stars, binary stars, and star clusters, to planetary

[11]ČT24/Czech Television article at `https://ct24.ceskatelevize.cz/veda/2945303-zive-sledujte-vyhlasovani-nobelovy-ceny-za-fyziku`.

[12]iDNES.cz at `https://www.idnes.cz/technet/veda/nobelova-cena-fyzika-2019.A191008_113110_veda_mla`.

or diffuse nebulas and galaxies. The nature of observed objects was described supplemented with talks on the evolution of the universe, research of extrasolar planets or life in the universe. The sky observations were concluded with the all-sky review of visible stellar constellations. As exoplanets have always been an interesting subject for people, the debate often shifted to the topic.

Another frequent activity intended as the outreach of the subject was the popular-educational lectures. It was presented in two similar versions. The first one with the title “Exoplanets – Distant Worlds without a Life (?!)” was focused on explaining the nature of exoplanets – what is a planet, how are the exoplanets different and the basic research history. Another part of the lecture was dedicated to Kepler Space Telescope and its discoveries, showing the diversity of known exoplanets and the possibility of finding another life in the universe. The second version of the lecture was titled “The Hitchhiker’s Guide to the Exoplanets”. It was created in 2019 for the Nobel Prize lecture and its focus was shifted more to the research methods, space missions and their techniques of the observations and the basic introduction to the search for life in the universe with an accent on the search for liquid water.

Approximately twenty lectures were given. The typical length of the lecture was about an hour. Most of them were presented for high school students, for example – several were presented at the FYKOS physics camps for talented student[13], another one was joined with the excursion of Perek 2m telescope at the Ondřejov observatory (the lecture and the excursion were part of the event called Week of Applied Physics in November 2017[14]). Two lectures were given at the FKS Summer School for high school students in Bratislava, Slovakia.

Other lectures were designated for the general public[15]. Two special talks were given in cooperation with organization Science to Go (`sciencetogo.cz`). The first one was the Nobel Prize lecture given to the public after the 2019 Nobel Prize laureates were announced. The lecture was shorter with time dedicated to questions from the audience. It was recorded and the record was later uploaded to YouTube[16]. The second talk was given during the COVID-19 pandemic in September 2020 as part of a series of short lectures (up to 15 minutes) called “Dotazovna” (open translation as “Questionnaire”). It was live-streamed and later archived on Facebook[17].

The important part of the outreach focused on high school students were the workshops with more hands-on experiences. The objective was to allow students to try real scientific work, with data processing and results analysis. These activities are thoroughly described in chapter 5.

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[13] More information at `https://fykos.org/events/camps/start`.

[14] More information at `https://fykos.cz/rocnik31/tsaf/start`.

[15] `http://www.astrokysuce.sk/index.php?option=com_content&view=article&id=263:prednaska-exoplanety-co-skryvaju-vzdialene-svety-2016&catid=10&Itemid=104`

[16] Information about the lecture at `https://sciencetogo.cz/events/detail?id=42`, record on YouTube available at `https://www.youtube.com/watch?v=2aae1lK3_ro&ab_channel=SciencetoGo%21`.

[17] Available at `https://www.facebook.com/watch/?v=1044104852691094`.

## 4.5 Proposed outreach activities

When planning outreach activities, the foremost task is to consider the audience and the main purpose of the particular activities. As described above, the activities can have various forms and topics. Choosing the audience dictates the form of the activity and its difficulty, as it differs when it is addressed to the general public and when it is intended for students of elementary school. For example, activities meant for children are preferred to have a game character, they should support the imagination and hands-on experience. On the other side, talks and lectures for the academic community or astronomy enthusiasts can give more detailed information on the topic.

The main purpose or the topic of the event should guide the contents of information given in the lecture and their depth in detail. For example, when presenting general information on exoplanets a basic overview should be presented. On contrary, when presenting future research goals and challenges with the purpose to receive support (e.g. financial funding or instrumental support) the focus shall be set to show the potential of the proposed project.

To utilize all the possibilities the subject of exoplanet research is offering, it is very important to use all forms of outreach activities. With this in mind, the following plan was created. Its purpose is to prepare the promotion of the PLATO space mission and the following ground-based research conducted at the Astronomical Institute of the Czech Academy of Sciences. It has two main objectives. The first is to demonstrate the importance of the mission (especially when financed from public resources as the in case of PLATO) and to gain support for future involvement in the next missions. The second objective is to use the expected interest in the PLATO mission and the exoplanets in general for further promotion of the research field.

### 4.5.1 In-person activities for general public

Outreach for the general public provides the biggest variety of possible activities. The bases are the popular-educational lectures about exoplanets. They may be organized separately from other activities or joined with various events, where the exoplanet is not the main subject. A previous promotion on an appropriate level is optimal for increasing attendance.

Apart from the other already mentioned forms – articles, interviews about the exoplanetary research, educational videos etc. – a collaboration with educational institutions, museums and planetariums can be beneficial. Organization of the various events co-organized with mentioned institutions may produce atypical outreach activities and help with the advertisement thanks to the wider coverage.

One such event could be the “Exhibition of Exoplanets” – an art or photo collection on exoplanet research. With rising numbers of directly imaged exoplanets, a combination of real photos and model or artistic images of various exoplanets could be presented. The exhibition could be supplemented with a lecture or interactive presentation on the subject.

### 4.5.2 Marketing activities

The media presence is necessary to raise awareness of the subject. This includes TV interviews, articles informing about new discoveries and lectures as part of different events and activities not exclusive to the subject of exoplanets.

A good approach is to publish a popular-educational article or short text on every research paper published in scientific magazines. Articles should explain the research with simple language accessible to the public. These materials can be shared on social media, sent to the TV or the newspapers or they can be offered to various web portals. This method helps to promote the research done at the institutions, which is useful for general outreach.

A particularly strong should be presence on social media. Not only they are the leading platform for approaching students and young people, but they are also becoming the channel used for contacting the media, various companies and organizations. With this in mind, a good appearance on chosen social media should be fundamental. It is open for consideration, depending on the human resources, whether to create a new channel or use the existing ones. For social media algorithms to promote the content or the channel as a whole, it is crucial to post daily. For good and rich content, an ideal combination is the author's own content and the one shared or translated from foreign sites, raising international collaboration as well.

### 4.5.3 Activities for children and high school students

The activities for children, especially those attending elementary schools, need to be playful and interactive. Excursions to the observatories and planetariums and the night sky observations usually offer this. Many institutions prepare dedicated programs presented in a more simple way, with animations and colourful pictures. For many children, astronomy is an exciting subject with exoplanets not lacking behind. Therefore, they can be included in the content.

In Slovakia, there is an engaging activity for elementary school students – a competition called "Vesmír očami detí" (open English translation "Space through children's eyes") organized by the Slovak Central Observatory Hurbanovo[18]. It is an art competition, children submit their artworks of various types, such as drawings, sculptures or models. For young children, it is an engaging form of expression, where they can practice their imagination. A similar competition can be prepared with the theme of exoplanets. An example assignment can have the title: "How does your dream exoplanet look like?". After children create their artwork, a debate can be held to discuss their ideas and to show them some illustrations of the exoplanets.

For high school students, a variety of activities can be organized. Most of them were already presented in previous sections (lectures, excursions, night sky observations etc.). Usually, the form does not need to change, only the content and its difficulty should be specially adjusted to the audience. Since high school students (in their senior year at the latest) are choosing their future studies at the university, general science outreach is important. It can show them the

[18]More information about the competition available at `https://www.suh.sk/organizujeme/sutaze/vesmir-ocami-deti/`.

possible carrier in science, which may not be clear and accessible at first given the exceptionality of this profession. Therefore, the outreach has yet another important function, the exoplanet outreach not leaving out.

More specialized activities such as seminars and workshops on exoplanet observations or data processing can be prepared for talented high school students who are interested in astronomy, physics and STEM subjects. Activities described in chapter 5 are the specific example. These activities can help talented students to make a final decision to follow the scientific carrier, giving the activities special importance.

### 4.5.4 College students

The university students represent a special group, especially the students of astronomy, physics and natural sciences in general as well as students of the STEM programs. These individuals may directly contribute to the research when choosing to specialize in the research of exoplanets. Of course, since the choice of the study program is often made before entering university studies, the outreach has the biggest impact on students at the high school (as described above). Another phase of the selection of future specialization is usually at the end of the bachelors (or undergraduate) studies when students choose the topic of their bachelor's thesis[19]. Choosing the research field may also happen at the beginning of the master studies.

Either way, it is important to present to students the possibilities and main challenges of exoplanetary research. The focus should be as well on the actual work being done – description of the nature of observations, data processing and research methods. This varies depending on the research objectives and the methods used at the given institution. Students may prefer to try out the research through some sort of internship. In such cases, it is vital to supervise them professionally. The work may be difficult and overwhelming at first, as several competencies and skills need to be learned. Scientific methods, computer skills and working habits need some time to be adopted. The lack of supervision and assistance may lead to a loss of interest from students.

In a general outreach dedicated to college students, more in-depth talks may be chosen, as general academic education should prepare students for more complicated terminology and the understanding of the research methods.

## 4.6 Useful sources of information

When doing the science outreach, it is important to work with the sources. As the research field covers a large area, the audience could be interested in more information, interesting facts and deeper self-study of the topic. Definitely, it should be encouraged to do so. Therefore, here are presented several useful sources[20]. Some of them are helpful for gaining a general overview of the exoplanets as they contain a nice summary of the basic knowledge. Others may

[19]The selection of the topic is usually done a year prior to the graduation, so it is important to get to the students soon enough.

[20]It is s selection based on the author's preferences, therefore it may be subjective. It cannot be considered as a complete list of the sources.

offer interesting facts via an educational form or precise statistics and the latest findings. The sources are divided into two groups according to the language they are written in.

### 4.6.1 International sources

Probably one of the best sources of information is **Wikipedia** – the free online encyclopedia. It is a well-known source of knowledge, especially among students. It is edited freely by anyone who likes to contribute, but it does not lower the value of information located there. Actually, the Wikipedia pages on exoplanets [111] are perfect for starting with the self-study. There is a lot of basic information on the main page about the subject. It is nicely divided into sub-chapters, going through the topics of the definition of exoplanets, history of the detection, detection methods, describing the formation and evolution of planets, main characteristics and it touches even the habitability of exoplanets. Each sub-chapter provides links to other pages, creating a dense network of sub-pages on the topic. There are lists of planets discovered sorted according to the date of discovery or the habitability, various historical charts etc. It is completed with many pictures, videos and graphs. A huge advantage of Wikipedia is the work with the sources. Nowadays, most of the information included on the pages is linked to its source. At the end of each article, there is a complete bibliography. Not only it gives an opportunity to get to the original material, but it also teaches visitors ethical principles of working with the information. Wikipedia pages on exoplanets are a great entry point for studying as well as a useful source of factual information and direct sources for researchers.

A very precise source of statistical information on numbers of the exoplanets and their characteristics is portal `exoplanet.eu` – **The Extrasolar Planets Encyclopaedia**. It contains most of the information about all known exoplanets, keeping count of the confirmed detections. There are three numbers – the number of discovered exoplanets, planetary systems and multiple-planet systems in the database. It was established in 1995 and it is developed and maintained by the exoplanet TEAM, which keeps it up to date with frequent updates.

No surprise **NASA** offers the beautiful **web pages** dedicated to exoplanets – `exoplanets.nasa.gov`. They offer image-full and engaging web pages. Interesting is the historical timeline or the gallery of "strange new worlds". The count of the confirmed exoplanets can be found there as well. Additional information can be found on the pages dedicated to a particular mission (like Kepler or TESS). In general, these web pages are an excellent example of exoplanet outreach.

Among the NASA web pages, a special place holds the **NASA Exoplanet Archive** (under the NASA Exoplanet Science Institute [70]). Its exoplanet and candidate statistics show detailed information about the research status, specializing in the statistics of the exoplanet candidates discovered by the space missions (mostly Kepler/K2 and TESS). There are stated also the numbers of exoplanets by the detection method, radius or mass statistics. Each parameter or category can be filtered in the complete list of the discovered exoplanets with known characteristics.

**Space.com** (`space.com`) is a portal promoting space exploration and presenting diverse astronomy news. A large portion of the articles is dedicated to exoplanets. They are well written, summarizing research papers and informing about new advances or recent activities of the space missions. The web is full of nice pictures providing help to imagine the facts described in the text.

Another portal worth mentioning is **Sky & Telescope** (`skyandtelescope.org`) providing useful information for astronomical observations and updates on the night sky objects. There are numerous articles about astronomical news, observational techniques and information about telescopes and other necessary tools useful for both professional and amateur astronomers. All information can be applied to the exoplanet observations.

### 4.6.2 Local sources in the Czech

One of the most popular web portals dedicated to astronomy and its outreach is the **web of the Czech Astronomical Society** `astro.cz`. There are various news and information published daily on the web pages – astronomy news (local as well as foreign), updates on space missions, beautiful pictures and information on various activities and events organized in the Czech Republic. Quite useful for all astronomers is the weekly sky report informing about the upcoming week's night sky events, positions of the planets and other major objects, planned launches of space missions and important anniversaries. There is often information about exoplanet research on the pages, with a special category dedicated to it between the articles.

In 2009, web pages specially dedicated to the topic of exoplanets were created. It was the first web of its kind in the Czech Republic. It was created on the occasion of the International Year of Astronomy (the event was coordinated by the IAU and it was endorsed by UNESCO)[21]. The web is called **Exoplanety.cz** (`exoplanety.cz`) and it was alive until February 2022, when the new articles stopped appearing on the portal. The reason is unknown to the author of this thesis. However, when alive, the web pages were an excellent source of up-to-date information on exoplanetary research. The articles were written in an easy style, often summarizing research papers, making them more accessible for all astronomy enthusiasts.

Another portal dedicated to strengthening the involvement of the Czech Academy of Sciences in space exploration is called **Vesmír pro lidstvo** (in open translation Space for mankind, accessible at `vesmirprolidstvo.cz`). Exoplanets are not its main focus. However, there is a lot of valuable information to be found on the subject of space missions – especially those with local involvement, organized outreach events and important discoveries often connected to exoplanets.

As well as for the English **Wikipedia pages, the Czech version** is a good entry point with a similar structure. It differs only in the depth of information, as the English version is more extensive and more detailed. However, it still offers valuable information for Czech-speaking readers.

[21] Several media informed about the web when created, for example, Novinky.cz, information retrieved on December 20, 2022, from `https://www.novinky.cz/clanek/internet-a-pc-cesti-astronomove-spustili-portal-o-zivote-ve-vesmiru-40218065`.

# 5. Hands-on activities for high school students

Activities described in this chapter were prepared for high school students and then conducted by the author of this thesis. In line with the plan presented in sub-chapter 4.5, they were targeted to talented students, who showed an interest in physics and astronomy. The purpose of the activities was to introduce them to the subject of exoplanets and to present to them the fundamental research procedures. After familiarizing themselves with the basic information, they were supposed to learn various methods of research, above all the photometric method (transit photometry) and the radial velocity measurements. They were also to learn the observational techniques, target selection and correction images and spectra preparation. The obtained data were to be used for basic data processing.

Activities are listed in both chronological order and by difficulty level, as the complexity was increasing purposely in time. Especially the data processing pipeline is the most difficult of the activities due to the technical and coding skills necessary to adopt. The method of data processing for RV measurements is special for its software complexity. Some of the skills needed are acquired only through experience which takes time to get.

In the final sub-chapter, all the activities are evaluated and compared to each other. Based on the results several improvements are proposed.

## 5.1 The Science Week

The first activity designed for talented high school was a so-called mini-project – an engaging part of the program at the 2018 edition of The Science Week[1] at the Faculty of Nuclear Sciences and Physical Engineering of Czech Technical University in Prague (FNSPE CTU). The event is annually organized by the faculty since 1999. It consists of various activities and lectures with educational and outreach purposes, promoting the carries in science and the faculty as such.

The Science Week was organized from Sunday, June 17, to Friday, June 22, 2018. Two parts of the program were connected to the subject of exoplanets, the first being the mini-project. The second activity was an excursion at the Ondřejov observatory of AI CAS.

The mini-project is a short science project done by a small group of students (usually 2 or 3). They can choose the topic of the project. Throughout a few days student work with a supervisor on the given task. After completing it, they write a short scientific paper for The Science Week's magazine and present the result in front of other students.

In 2018, a mini-project dedicated to exoplanet research was called "Preparation of the follow-up observations of exoplanet candidates discovered by the TESS mission". The objective of the project was to work with the database of TESS candidates and select the best targets for observations with Perek 2-meter telescope at the Ondřejov observatory. The OES spectrograph was to be used for

[1] The web pages accessible at `https://tydenvedy.fjfi.cvut.cz/`.

obtaining the echelle spectra for the RV measurements. The aim of the follow-up observations was to confirm the exoplanet or a false-positive. One of the project outputs was to be the observational plan for the follow-ups of selected targets. Two high school students participated in the project.

On the first day, a lecture was given to students providing general information and describing the research on exoplanets and its objectives. It was especially focused on the research methods and the observational techniques and requirements. After the lecture, a supervisor gave a commented walk-through of the data. Students could examine the data – both scientific images of the studied target and correction spectra necessary for the data processing. After a briefing on the task, they could start the work on the project.

Most of the first day was dedicated to the work on the project. Students were supervised by a supervisor. Later that day they attended a lecture on scientific presentation (given by scientists from the faculty participating in The Science Week). Students were supposed to learn how to present their results and how to write a contribution to the magazine.

The next day was fully dedicated to working on the project and its outputs. Students could communicate with a supervisor. At the end of the day, they were supposed to submit the final article. The last two days of the program were dedicated to the talk presentations of the results. Students were divided into several groups and they presented their results to fellow participants of The Science Week.

To help them with work on the project, students received several support materials – slides from the presentation used at the given lecture, the final report of the scientific project done on a similar subject (Characterization of exoplanetary candidates from mission K2 — measurements of radial velocities, Dupkala 2018 [24]) and formulas for calculation of the exoplanet mass from the RV measurements (see the attachment A.1, updated and translated from the Czech language). The last one was used to understand what are the key parameters needed from the obtained RVs. They also got the example observational plans from previous nights. To search for the targets, they were introduced to the NASA Exoplanet Archive [70].

The final article (four pages long) submitted to the magazine together with the slides of the students' talk presentation can be found in The Science Week archives (Nováčková & Mikeska 2018 [72], [73]). Program of the whole week, guest lectures and the list of all mini-projects can be found on the web pages as well [100].

The excursion to the Ondřejov observatory was organized on a day before the talk presentations. A group of 16 students visited the dome of the observatory, where they saw the Perek telescope, the OES spectrograph and the control room. They visited an observatory museum and also attended a lecture on exoplanets. Students participating in the exoplanet mini-project did not have to participate in the excursion, as the destination was chosen independently on the subject of the project.

### 5.1.1 Evaluation of the Science Week

The mini-project with the subject of preparation of the follow-up observation of exoplanetary candidates can be evaluated as successful. In a relatively short time dedicated to the work on the project, students were able to understand the subject, work with the support materials and get familiarized with the database of exoplanet candidates. The final results were of very good quality with a suitably prepared observational plan. General feedback from all students was positive as well[2].

The only shortcoming of the activity is the lack of follow-up work with students. Especially valuable could be to use the result of the project for actual observation. Students could be invited to observe the targets themselves. This did not happen for several practical reasons. At first, the program of The Science Week did not allow this immediately after the work on the project. Due to the date of the event at the end of school year, it was not possible to organize the observation on the following days as well, since students had to attend the school in order to close the classification. If organized again in the future, the follow-up observation with participating students could be pre-planned and organized shortly after The Science Week.

## 5.2 T-Excursions

The second activity dedicated to exoplanetary outreach and development of talented high school students was the T-Excursion to the Ondřejov observatory. The concept of interactive excursions to the research institutions comes from Talnet, a non-profit organization under the National Pedagogical Institute of the Czech Republic[3]. T-Excursions aim for students not only to visit the facilities but rather to engage in simple research activities as well with professional mentors.

Student participation consists of three phases. The first one – a preparatory part includes a week or two of home study using the study materials and work on several exercises or tasks. These are evaluated by a supervisor before the excursion itself (the second part) providing a student with important feedback on their preparation. The excursion is usually a full day at the research institution. During the visit, students perform a prepared experiment, measurements or observations. After the excursion, they process the obtained data and describe the whole experience in the so-called T-report, which is the third part of the T-excursion. It can have any form, from an article to a video report etc.

For the T-Excursion at the Ondřejov observatory, a two-day program was prepared, so the students could participate in the night observation with the Perek 2-meter telescope. The aim was to obtain the data which they would later process and study. However, the COVID-19 pandemic forced the plan to be changed, as the pandemic situation did not allow in-person activities. Therefore, all the activities had to be organized online. This also led to the change of the tasks prepared for the excursion and overall approach to it as the observations could not

[2]The feedback from the 2018 Science Week is available at `https://tydenvedy.fjfi.cvut.cz/2018/web/index.php?p=feedback-vyhodnoceni` (retrieved on January 1, 2023).

[3]The web pages available at `https://en.npi.cz/`.

be done with the participants[4]. For communication, submitting of the students' work and online meetings during the T-Excursion, the Google Classroom platform was used.

The chosen topic of the T-Excursion was transit photometry. Even though it is not the leading research method at the Astronomical Institute for exoplanet research, it offers easy work with the data (much easier than the RVs), which is a key factor for short-term projects.

For the preparatory phase, study materials were prepared for participants. They were prepared by student members of the exoplanet group at AI CAS[5]. These materials cover the subjects of electromagnetic radiation, basic information about the studied objects (stars, planets and exoplanets), transit photometry and observations using the Perek telescope. Together with the materials the homework tasks were prepared (by the author of this thesis) (see the attachment A.2). Their main objective was to make students think about the information learned thanks to the self-study and to use their creativity and searching skills to find the answer to the interesting questions. Students were asked about the closest exoplanet to Earth, the parameters important for target selection (both instrumental parameters as well as the weather conditions) and the main planetary parameters important when searching for life in the universe. After completing the tasks, students got feedback on their work, and most of them handled it well.

As mentioned before, the excursion itself took place "online" via Google Classroom in the form of an online meeting of all participants and lecturers. It was held from Tuesday to Wednesday, November 27 to 28, 2020, as the program started on the afternoon of the first day and continued through the evening. The second part started the next morning with the work on data, which was evaluated and discussed with participants later that afternoon. In total 7 students participated in the T-Excursion[6].

The program started with the introductory lecture (approx. 45 minutes, lecturer Dupkala D.) providing general information about exoplanets, methods of their research etc. The lecture was followed by a debate with participants (approx. 30 min) on the target selection and parameters necessary for the preparation of the observational plan. This activity was based on the homework done by students. For a special introduction to the Perek telescope, a video excursion was prepared for participants of the T-Excursion to have at least a "virtual" look at the telescope. The video was prepared in the Slovak language by Daniel Dupkala and Ján Šubjak and it was posted on YouTube where it is publicly available[7]. Participants could watch the video during a break before the last part of the evening program – a workshop on data analysis and evaluation (approx. 30 minutes). Supervisors showed students how to read the data – light curve figures – and how to get the basic information and parameters out of them. It was a direct preparation for the practical part of the excursion.

[4]The telescope can be used in the mode of remote control, but it is not as entertaining and engaging as for the on-site observation.

[5]Blažek M., Dupkala D., Špoková M. and Šubjak J. participated in the preparation of the materials.

[6]A few more students registered for the program, but later did not take part in it (some of them did not participate due to scheduling problems or school duties).

[7]Video is available on YouTube at `https://www.youtube.com/watch?v=g5hgRKG8uRA&t=6s&ab_channel=J%C3%A1n%C5%A0ubjak` (retrieved on December 29, 2022).

At the end of the workshop, students received the data for the practical assignment. The data contained a light curve of the exoplanet transit of the WASP-36 star. Based on the information learned in the preparatory phase as well as during the previous program of the excursion, they were supposed to work out several tasks on the exoplanet characterization (see the attachment A.3). The tasks included the determination of the transit parameters (e.g. transit duration), calculation of exoplanet parameters (planetary radius and distance from the host star) and consideration of its habitability.

In the afternoon, the results of the students' work were discussed. During the debate, they presented their work with the possibility to correct or better understand some unclear tasks (45 minutes). The conclusions were later used for their final reports. The program of the excursion was concluded with a presentation and following debate on the topic of the search for life in the universe (circa 45 minutes with extra time for additional questions, lecturer Dupkala D.).

After the excursion, students had two weeks to complete their final reports. The form of the report or its content was not specified, the report should describe their experience on the excursion. Therefore, they could choose their preferred form and use their creativity. The only condition was to mention the results of the practical part of the excursion.

From the received reports, one of them was created as a video-simulation with commentary, another as a simple poster with the results of the practical assignment, and others were written as short articles. One report was written in a form of diary, describing the whole T-Excursion from the participant's point of view and presenting the results. The reports were internally evaluated, as the best one of them was classified as the "best report competition" from the autumn round of T-Excursions. From all the chosen reports, the one chosen as the best from the exoplanetary T-Excursion was later awarded a honourable mention.

### 5.2.1 Evaluation of the T-Excursions

General feedback from the participants was highly positive. Even though lacking the in-person meeting and visit to the observatory, students found the program prepared for the T-Excursion interesting and interactive. In the questionnaire survey, average satisfaction with the form of the T-Excursion was 5.0 (on a scale from 1 to 6, where 6 is the best rating), and the content of the excursion had an average rating of 5.1. The scope of the event (a range or volume of the content) was rated 4.3 and the difficulty of the preparatory part and the excursion itself were rated 2.1 and 2.4 respectively. The last three parameters were explained in the commentaries as affected by the online form of the event.

Given the circumstances, the excursion may be considered successful. It has fulfilled its objectives (presenting the subject to talented students and their active involvement), even though the limited options due to the pandemic situation. The whole idea of an excursion and real astronomical observation is difficult to implement without an in-person visit to the observatory.

The selected method – transit photometry – proved to be suitable for working with talented high school students. Generally, participants did not have problems understanding the physics or the basic principles behind the method. For future work with students, especially for mid-term or long-term projects, data processing could be possible. Based on these conclusions, students could try real exoplanet research. The project could start with transit observations. Students could later process the obtained data and further analyse them. From the result, they should be able to determine the basic parameters of the exoplanet.

## 5.3 Data processing pipeline

The third project focused on working with talented high school students was a special initiative to teach them data processing. The chosen method was the Doppler spectroscopy - radial velocity measurements, as it is a dominant method of exoplanetary research at the Ondřejov observatory at AI CAS.

A long-term objective of the initiative was to prepare students to the level that they do the target observations and work on the data processing and evaluation independently. To manage the whole process of data gathering and analysis, several steps are necessary to learn. At first, the methods of observation together with target selection and preparation of the observational plan (including all the correction images). The next step is the reduction and extraction of the spectra. Its results are the normalized spectra with identified spectral lines ready for determination of the RVs and further analysis. Calculation of the RVs and analysis of the RV phase diagrams is the last step of the process.

Managing all the steps is rather difficult and it takes a long time to master. Therefore, the primary initiative was aimed at the data reduction and possibly determination of the RVs. This includes the general overview of the data package – understanding of the target selection and correction frames necessary for the reduction. It is the most complicated part of the process, yet it is possible to divide it into several routine procedures easier to learn. The data processing does not require a too high level of subject knowledge (in comparison to the correct RVs calculation).

Another advantage of the selected assignment is the option for students to work on data independently with remote supervision. That is the opposite of observational training, which was planned for the second stage of the project. That would include several nights of observations with the Perek telescope. The in-person presence of students could cause some organizational difficulties because of the school attendance and commuting to Ondřejov. Therefore it was postponed to the second stage. As the RVs calculation and analysis require some additional knowledge of the subject (even though still manageable for a high school student), it was postponed to the further stages of the project as well.

For the majority of data processing, IRAF software[8] is used. The software itself is old and complicated, however, can do quite advanced operations with data. Its installation and use are difficult, especially the first set-up. To help students with the learning process, several manuals and scripts were prepared. In general, the scripts are used for faster and routine data processing (an example script is shown in the attachment A.4). The scripts were prepared by members of the exoplanet group at AI CAS, above all Dr. Marek Skarka, who supervised the

[8]Image Reduction and Analysis Facility was originally written by the National Optical Astronomy Observatories (NOAO) in Tucson, Arizona. After its development stopped in 2013, the maintenance has been done by the IRAF community. It is available at `https://iraf-community.github.io/` (retrieved on December 30, 2022).

creation of the OES pipeline (with a significant contribution to the preparation of the scripts by the author of this thesis). The data processing procedure described in the manual (attachment A.5) is based on the video-commentaries of Dr. Skarka and the previous research (described in Dupkala 2018 [24], Dupkala 2019 [25] or Kabáth et al. 2020 [45]). The manual itself was written down by the author of this thesis.

In total 16 students participated in the project testing. All of them were students of the Prague grammar schools, and most of them were in their 1st or 2nd year. The project was conceived as a workshop on data processing and it took place on April 22, 2022. The workshop started with an introductory lecture about the exoplanets and the research methods, especially Doppler spectroscopy. As for the activities before, participants learned the history of the research, its goals and the main tasks. There was room for questions from participants and further explaining of some unclear or more interesting points.

The lecture was followed with detailed descriptions of the observational techniques and the target selection. It gave students a basic knowledge of correction images necessary for a complete reduction and extraction of the spectra. Examples of all types of used correction frames were shown. Images of the raw spectra were shown as well and they were compared with the reduced spectra, so students could see the difference. Finally, normalized extracted spectra were shown as the desired results.

After the first batch of theoretical information, students were instructed to install the necessary software and copy all scripts for data processing. This met with several technical difficulties, which delayed further progress. As the partial solution, students were divided into groups so they could continue with the data processing. Using the prepared manuals and scripts, the first part of the spectra reduction was explained and presented. The processing was done on the data sample chosen for the testing[9]. As the supervisor presented the method, the student could simultaneously work on the same data sample.

During the workshop, only the first part of the spectra reduction was presented. As the whole data processing pipeline is several steps long (in sum 14 scripts are used to get the normalized extracted spectrum), the process was divided into several parts. Because of the amount of new information on the first day, students had some problems keeping up with the process. After the workshop, they could resolve the problems with the installation or retry the presented steps of the spectra reduction. Students could consider continuing with the project. Informal talks were led to get direct feedback from the participants' perspectives. The initiative was evaluated both from the supervisor's point of view as well as from the general point of view. This analysis has led to the suggestion for future improvements.

### 5.3.1 Evaluation of the data processing pipeline

In general, this initiative has turned out to be more complicated than expected. There were three main issues – the overall difficulty of the spectral data

[9]Spectra of the star TYC 1083-12-1 were used, providing enough spectral lines for optimal spectra extraction. They were taken on the night with good observational conditions (August 8, 2020). The spectra were chosen by Dr. Marek Skarka.

processing, the selection of participants and technical issues.

In general, the difficulty of the data processing pipeline was the biggest issue of the whole initiative. IRAF software is extremely difficult to use, often buggy and chaotic – the characteristics not suitable for the work with students in order to attract them to the subject of exoplanets. The spectral analysis is complicated and it takes time to get to the results. Therefore it is not well suited for engaging outreach activities.

Another issue was related to the selection of participants. Students who participated in the project were talented high school students. Some of them attended a physics curse at the Department of Physics Education at the Faculty of Mathematics and Physics of Charles University. The first problem with the selection was the young age of the participants, as most of them were students in the 1st or 2nd year of grammar school. However, data processing requires some level of experience in scientific methods and computer and coding skills, which most students lack at a young age.

Another problem was associated with the specialization of students – most of them were not specialized in astronomy or similar research fields. Therefore, they were less motivated to participate in the long-term project. A smaller number of participants is also necessary for more individual supervision. A group larger than 5 or 6 students is hard to navigate through the difficulties with usually occur during data processing.

The problems associated with the software installation and set-up were caused especially by the lack of computers operating on the Linux system and by the problems with the internet connection. Several offline sources of the data and software installation files were prepared (on USB portable devices etc.). However, the large number of participants at the workshop limited the possibilities and prolong the installation of the software. The lack of participants' experience of the work with the Linux system caused another delay and technical problems, which were too difficult to quickly eliminate.

In conclusion, the method of RV measurements proved to be the most difficult, offering limited room for work with high school students. To improve the results, the project should be carried out with a much smaller group of students or individuals. Also, they should have at least a minimal level of experience with the data processing methods necessary for the work. Ultimately, sufficient time must be dedicated to the training in order to master the data processing pipeline (especially if the participants are new to data processing of a similar nature).

## 5.4 Results and future improvements

After three various activities done with talented high school students, it is possible to evaluate and compare them. The level of difficulty and direct engagement is different, yet several conclusions can be brought. As the objective is to further involve high school students in data processing and real scientific work, the most important is the evaluation of the used research methods and their suitability for the projects working with high school students.

During The Science Week, students worked on the observational plans, studied the methods of target selection, the work with the archives, and the preparation for the scientific observations. There were no problems in the preparation for observations and students succeeded in their task. Therefore, high suitability can be concluded for the given topic. It is recommended to continue with similar activities and follow up on them with in-person observations and training in observational techniques. A reasonable objective – preparation of new astronomical observers – can be set for the future continuation of the project.

Based on the work done with participants of the T-Excursion, the transit photometry and especially the result evaluation and characterization of the exoplanet parameters can be considered another success. The photometry proved to be easy to understand and there were almost no problems with the analysis of the phase diagrams. As stated in the feedback received from participants, they would like to be engaged even further and work on more advanced research methods. Therefore, for future activities, full processing of photometric data could be undertaken – as a form of follow-up activity for interested participants. In contrast to the spectroscopic method, photometric images can be relatively simply processed using the Muniwin software[10], which is quite popular for reduction of the CCD camera images.

In future, both activities should be supplemented with in-person observations as they are not only the key element of astronomical research but an exciting and inspirational experience as well. The night observations have the potential to motivate students for further engagement.

The last initiative – processing of the spectral images – has met with several problems, the most significant being the entry barrier to the data processing. The currently used IRAF software, running on Linux[11] operating system, is complicated for students with no previous experience. In general, it takes time to familiarize yourself with the procedures and usage of the systems. This is not suitable for activities focused on talented high school students who are not completely dedicated to the subject of spectral analysis. Students of senior year or college students have a better predisposition for this task compared to younger students who participated in the testing run.

Based on these conclusions, the work with talented high school students should continue. From gained experience, it is possible to state that the development of proven activities will be beneficial for exoplanet research, general outreach and most importantly for students involved in these activities.

[10] The software is available at `https://c-munipack.sourceforge.net/` (retrieved on December 30, 2022).

[11] The software can be run using the virtual box in Windows, “simulating” the Linux operation system. However, the complications are not totally eliminated with this method.

# Summary

The extrasolar planets are one of the leading research fields in astronomy in the 21st century. They are also an attractive topic for scientific outreach. This thesis summarized the exoplanetary research and its outreach, with a focus on the Czech Republic and the mission PLATO.

In chapter 1 a history of the subject was summarized. From the ancient philosophical concepts to the first discoveries, important milestones were presented. The current status and future plans were described as well. In chapter 2 the basic research methods were presented with a special focus on transit photometry, Doppler spectroscopy (the radial velocity measurements) and direct imaging. The first two methods are often used in the Czech Republic, as was described in chapter 3. In addition to its scientific value, direct imaging is an important source of widely spread photos or models.

In chapter 4, possible approaches to exoplanet outreach were described. Several basic outreach activities were presented (e.g. lectures, public night sky observations, interactive exhibitions etc.) with emphasis on the work done by the author of this thesis. A plan for future activities was elaborated to promote the subject of exoplanets with the aim to raise general knowledge of the topic, to educate and entertain the general public and to present new scientific findings.

Special attention was paid to the talented high school students. As described in chapter 5, three main activities were conducted with the purpose to introduce them to exoplanet research with hands-on experience in astronomical observations and data processing. Various approaches and methods were used.

For future initiatives dedicated to working with talented students, several recommendations were made. Based on the comparison of the research methods, transit photometry is the preferred one due to its simplicity and easier data processing. The activities are suggested to cover an observational experience as well as the data processing and the evaluation of the results. Thanks to this approach students will be able to gain a comprehensive idea of exoplanetary research. These activities may be adjusted for the specific group of students or individuals to fit their age (i.e. level of knowledge and skill set), level of interest and previous experience.

In general, the result presented in this thesis will be used for future outreach on the subject of exoplanets. As the PLATO and ARIEL missions (both significant for the research) are prepared with the Czech participation, presented activities may be used to help to raise awareness of the missions and their value, as well as the importance of the Czech contribution to them.

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# References


[1] ANGLADA-ESCUDÉ G., AMADO P.J., BARNES J. ET AL. (2016): A terrestrial planet candidate in a temperate orbit around Proxima Centauri. *Nature* **536**, 437-–440

[2] ARTIGAU É., CADIEUX C., COOK N.J. ET AL. (2022): Line-by-line Velocity Measurements: an Outlier-resistant Method for Precision Velocimetry. *AJ* **164**, 84

[3] BAGLIN A., AUVERGNE M., BARGE P., et al. (2006): Scientific Objectives for a Minisat: CoRoT. *Proceedings of The CoRoT Mission Pre-Launch Status - Stellar Seismology and Planet Finding* (ESA SP-1306). Edited by Fridlund M., Baglin A., Lochard J., Conroy L., ISBN 92-9092-465-9 p.33

[4] Barnard's Star. [online] SIMBAD, Centre de données astronomiques de Strasbourg. Retrieved 2022-11-23 from `https://simbad.cds.unistra.fr/simbad/sim-id?Ident=BD%2B043561a`

[5] BENEDICT G.F., HARRISON T.E., ENDL M., TORRES G. (2018): A Mass for $\gamma$ Cep Ab. *Res. Notes AAS* **2** 2, 7

[6] BENEDICT G.F., MCARTHUR B.E., GATEWOOD G., et al. (2006): The Extrasolar Planet epsilon Eridani b - Orbit and Mass. *AJ* **132** 5, 2206–2218

[7] BEN-JAFFEL L., BALLESTER G.E. (2013): Hubble Space Telescope detection of oxygen in the atmosphere of exoplanet HD 189733b. *A&A* **553**, A52

[8] BORUCKI W.J. (2016): KEPLER Mission: development and overview *Rep. Prog. Phys.* **79**, 036901

[9] BOUÉ G., MONTALTO M., BOISSE I., et al. (2013): New analytical expressions of the Rossiter-McLaughlin effect adapted to different observation techniques. *A&A* **550**, A53

[10] BOUTAUD A.S., GIRARD CH. ET AL.: Sagascience – Exoplanets [online]. Copyrights CNRS/Sagascience. Retrieved 2022-11-19 from `https://sagascience.com/exoplanetes/en/`

[11] BOZZA V., MANCINI L., SOZZETTI A. (2016): Methods of Detecting Exoplanets. 1st edition, Switzerland: *Springer International Publishing*, ISBN 978-3-319-27456-0

[12] BUTLER R.P., MARCY G.W. (1996): A Planet Orbiting 47 Ursae Majoris. *ApJL* **464**, L153

[13] Caldwell D.A., Van Cleve J.E., Jenkins J.M. et al. (2010): Kepler instrument performance: an in-flight update. *SPIE Proceedings*, SPIE **7731**, 773117. Edited by Oschmann J.M. Jr., Clampin M.C., MacEwen H.A.

[14] Campbell B., Walker G.A.H. (1979): Precision radial velocities with an absorption cell. *Astronomical Society of the Pacific, Publications* **91**, 540-545

[15] Campbell B., Walker G.A.H., Yang S. (1988): A Search for Substellar Companions to Solar-type Stars. *ApJ* **331**, 902

[16] Čeman R., Pittich E. (2005): Rekordy: VESMÍR 1 Slnečná sústava. 2st revised edition, Bratislava: *MAGNUS PRESSS, a. s.*, ISBN 80-8067-148-6

[17] Charbonneau D., Brown T.M., Latham D.W., Mayor M. (2000): Detection of Planetary Transits Across a Sun-like Star. *ApJ* **529** 1, L45–L48

[18] Charbonneau D., Brown T.M., Noyes R.W., Gilliland R.L. (2002): Detection of an Extrasolar Planet Atmosphere. *ApJ* **568** 1, 377–384

[19] Chauvin G., Lagrange A.M., Dumas C. et al. (2004): A giant planet candidate near a young brown dwarf. Direct VLT/NACO observations using IR wavefront sensing. *A&A* **425**, L29–L32

[20] Choi C.Q. (2011, September 15): Planet Like 'Star Wars' Tatooine Discovered Orbiting 2 Suns. [online] *space.com*. Retrieved 2022-12-20 from `https://www.space.com/12963-tatooine-planet-2-suns-star-wars-kepler-16b.html`

[21] Cooper K. (2022, August 25): Possible water world spotted orbiting an alien star. [online] *space.com*. Retrieved 2022-12-20 from `https://www.space.com/ocean-world-habitable-zone-potential-detection`

[22] Currie T., Debes J., Rodigas T.J. et al. (2012): Direct Imaging Confirmation and Characterization of a Dust-enshrouded Candidate Exoplanet Orbiting Fomalhaut. *ApJL* **760** 2, L32

[23] Czech Astronomical Society (2004, September 4): První pozorování zákrytu hvězdy exoplanetou v České republice [press release]. Retrieved on 2022-12-15 from `https://www.astro.cz/clanky/exoplanety/prvni-pozorovani-zakrytu-hvezdy-exoplanetou-v-ceske-republice.html`

[24] Dupkala D. (2018): Characterization of exoplanetary candidates from mission K2 — measurements of radial velocities. Ondřejov. Student Faculty Grant summary, Charles University, Faculty of Mathematics and Physics. Supervised by Kabath P., Skarka M.

[25] Dupkala D. (2019): High resolution spectroscopy of exoplanets — tool for characterization. Ondřejov. Bachelor's thesis. Charles University, Faculty of Mathematics and Physics. Supervised by Kabath P.

[26] Ehrenreich D., Lecavelier Des Etangs A., Hébrard, G. et al. (2008): New observations of the extended hydrogen exosphere of the extrasolar planet HD 209458b. *A&A* **483** 3, 933–937

[27] Evans T.M., Pont F., Sing D.K. et al. (2013): The Deep Blue Color of HD 189733b: Albedo Measurements with Hubble Space Telescope/Space Telescope Imaging Spectrograph at Visible Wavelengths. *ApJL* **772** 2, L16

[28] Farihi J. (2016): Circumstellar debris and pollution at white dwarf stars. *New Astronomy Reviews* **71**, 9–34

[29] Gaffney V., Fitch S., Ramsey E. et al. (2013): Time and a Place: A luni-solar 'time-reckoner' from 8th millennium BC Scotland. *Internet Archaeology* **34**, `https://doi.org/10.11141/ia.34.1`

[30] Galicher R., Marois C., Zuckerman B., Macintosh B. (2013): Fomalhaut b: Independent Analysis of the Hubble Space Telescope Public Archive Data. *ApJ* **769** 1, 42

[31] Gaspar A., Rieke G. (2020): New HST data and modeling reveal a massive planetesimal collision around Fomalhaut. *PNAS* **117** 18, 9712–9722

[32] Gatewood G., Eichhorn H. (1973): An unsuccessful search for a planetary companion of Barnard's star BD +4 3561. *AJ* **78**, 769–776

[33] Gillon M., Triaud A.H.M.J., Demory B.O. et al. (2017): Seven temperate terrestrial planets around the nearby ultracool dwarf star TRAPPIST-1. *Nature* **542** 7642, 456–460

[34] Grygar J. (1996, September 5): První exoplaneta. [online] *Vesmír*. Retrieved 2022-12-21 from `https://vesmir.cz/cz/casopis/archiv-casopisu/1996/cislo-9/prvni-exoplaneta.html`

[35] Guenther E.W., Wuchterl G. (2003): Companions of old brown dwarfs, and very low mass stars. *A&A* **401**, 677–683

[36] Hatzes A.P., Cochran W.D., Endl M. (2003): A Planetary Companion to $\gamma$ Cephei A. *ApJ* **599** 2, 1383–1394

[37] HD 209458. [online] SIMBAD, Centre de données astronomiques de Strasbourg. Retrieved 2022-11-28 from `https://simbad.cds.unistra.fr/simbad/sim-basic?Ident=HD+209458`

[38] Henry G.W., Marcy G., Butler R.P., Vogt S.S. (1999): HD 209458. *IAU Circ.*, No. **7307**, #1. Edited by Green D.W.E.

[39] Henry G.W., Marcy G.W., Butler R.P., Vogt S.S. (2000): A Transiting „51 Peg-like" Planet. *ApJ* **529** 1, L45–L48

[40] Hershey J.L. (1973): Astrometric analysis of the field of AC +65 6955 from plates taken with the Sproul 24-inch refractor. *AJ* **78**, 421–425

[41] Howell E. (2021): NASA's superfast Parker Solar Probe just broke it own speed record at the sun. [online] In: *space.com*, November 23. Retrieved 2022-05-15 from `https://www.space.com/parker-solar-probe-sun-speed-record-november-2021`

[42] IAU NameExoWorlds (2022) [online]. Retrieved 2022-12-19 from `https://www.nameexoworlds.iau.org/`

[43] Jacob A.P., Bedding T.R., Robertson J.G., Scholz M. (2000): Wavelength dependence of angular diameters of M giants: an observational perspective. *MNRAS* **312** 4, 733–746

[44] Kabáth P., Chaturvedi P., MacQueen P.J. et al. (2022): TOI-2046b, TOI-1181b, and TOI-1516b, three new hot Jupiters from TESS: planets orbiting a young star, a subgiant, and a normal star. *MNRAS* **513** 4, 5955–5972

[45] Kabáth P., Skarka M., Sabotta S. et al. (2020): Ondřejov Echelle Spectrograph, Ground Based Support Facility for Exoplanet Missions. *PASP* **132** 1009, 035002

[46] Kabáth P., Žák J., Boffin H.M.J. et al. (2019): Detection Limits of Exoplanetary Atmospheres with 2-m Class Telescopes. *PASP* **131** 1002, 085001

[47] Kalas P., Graham J.R., Chiang E. et al. (2008): Optical Images of an Exosolar Planet 25 Light-Years from Earth. *Science* **322** 5906, 1345

[48] KESPRINT web pages. [online] Retrieved on 2022-12-16 from `https://kesprint.science/`

[49] Kiefer F. (2019): Determining the mass of the planetary candidate HD 114762 b using Gaia. *A&A* **632**, L9

[50] Kolinski D. (2005): The Search for Exoplanets: History of the Search, [online]. Retrieved 2022-11-18 from `https://www.hao.ucar.edu/research/stare/search.html`

[51] Konacki M., Wolszczan A. (2003): Masses and Orbital Inclinations of Planets in the PSR B1257+12 System. *ApJ* **591**, L147

[52] Koubský P., Mayer P., Čáp J., et al. (2004): Ondřejov Echelle Spectrograph – OES. *Publ. Astron. Ins. ASCR* **92**. 37–43

[53] Lagrange A.M., Gratadour D., Chauvin G. et al. (2009): A probable giant planet imaged in the $\beta$ Pictoris disk. VLT/NaCo deep L'-band imaging. *A&A* **493** 2, L21–L25

[54] Lagrange A.M., Meunier N., Rubini P. et al. (2019): Evidence for an additional planet in the $\beta$ Pictoris system. *Nature Astronomy* **3**, 1135–1142

[55] Latham D.W., Mazeh T., Stefanik R.P. et al. (1989): The unseen companion of HD114762: a probable brown dwarf. *Nature* **339**, 38–40

[56] Lawton A.T., Wright P. (1989): A planetary system for Gamma Cephei? *JBIS* **42**, 335–336

[57] Lea R. (2022, December 20): Possible water world spotted orbiting an alien star. [online] *space.com*. Retrieved 2022-12-20 from https://www.space.com/potentially-habitable-earth-like-worlds-cosmic-backyard

[58] Legér A., Rouan D., Schneider J. et al. (2009): Transiting exoplanets from the CoRoT space mission. VIII. CoRoT-7b: the first super-Earth with measured radius. *A&A* **506** 1, 287–302

[59] Ligi R., Mourard D., Lagrange A.M. et al. (2012): A new interferometric study of four exoplanet host stars: $\theta$ Cygni, 14 Andromedae, $\upsilon$ Andromedae and 42 Draconis. *A&A* **545**, A5

[60] Lubin J., Robertson P., Stefansson G. et al. (2021): Stellar Activity Manifesting at a One Year Alias Explains Barnard b as a False Positive. *AJ* **162**, 61

[61] Marcy G.W., Butler R.P., Williams E., et al. (1997): The planet around 51 Pegasi. *ApJ* **481**, 926–935

[62] Marois C., Macintosh B., Barman T. et al. (2008): Direct Imaging of Multiple Planets Orbiting the Star HR 8799. *Science* **322** 5906, 1348

[63] Marois C., Zuckerman B., Konopacky Q.M. et al. (2010): Images of a fourth planet orbiting HR 8799. *Nature* **468** 7327, 1080–1083

[64] Mayor M., Queloz D. (1995): A Jupiter-mass companion to a solar–type star. *Nature* **378**, 355–359

[65] Mayor M., Queloz D.,Marcy G. et al. (1995): 51 Pegasi. Edited by Marsden B.G., *IAU Circ.* **6251**, 1

[66] Mohanty S., Jayawardhana R., Huélamo N., Mamajek E. (2007): The Planetary Mass Companion 2MASS 1207-3932B: Temperature, Mass, and Evidence for an Edge-on Disk. *ApJ* **657** 2, 1064–1091

[67] Monteiro M.J.P.F.G., Lebreton Y., Montalban J., et al. (2006): Report on the CoRoT Evolution and Seismic Tools Activity. *Proceedings of The CoRoT Mission Pre-Launch Status – Stellar Seismology and Planet Finding* (ESA SP-1306). Edited by Fridlund M., Baglin A., Lochard J., Conroy L., ISBN 92-9092-465-9 p.363

[68] Motalebi F., Udry S., Gillon M. et al. (2015): The HARPS-N Rocky Planet Search. I. HD 219134 b: A transiting rocky planet in a multi-planet system at 6.5 pc from the Sun. *A&A* **584**, A72

[69] Murphy S.J., Bedding T.R., Shibahashi H. (2016): A Planet in an 840 Day Orbit around a Kepler Main-sequence A Star Found from Phase Modulation of Its Pulsations. *ApJL* **827** 1, L17

[70] NASA Exoplanet Science Institute (2020): Planetary Systems Table [online]. B.m.: IPAC. Retrieved 2022-11-27, available at https://exoplanetarchive.ipac.caltech.edu/docs/counts_detail.html, doi:10.26133/NEA12

[71] NASA's Kepler Mission Discovers 461 New Planet Candidates, (2013, January 11), [online] *NASA*. Retrieved 2022-12-21 from https://www.nasa.gov/mission_pages/kepler/news/kepler-461-new-candidates.html

[72] Nováčková B., Mikeska M. (2018, June 22): Příprava follow-up pozorování kandidátů na exoplanety objevených vesmírnou misí TESS. [online] Proceedings of the Science Week of the FNSPE CTU. Supervised by Dupkala D. Retrieved 2023-01-01 from https://tydenvedy.fjfi.cvut.cz/2018/cd/sbpdf/TESS.pdf

[73] Nováčková B., Mikeska M. (2018, June 22): Příprava follow-up pozorování pro misi TESS. [online] Slides of the talk presentation at the Science Week of the FNSPE CTU, supervised by Dupkala D. Retrieved 2023-01-01 from https://tydenvedy.fjfi.cvut.cz/2018/cd/pres/TESS.pdf

[74] Nutzman P., Charbonneau D., Winn J.N., et al. (2009): A Precise Estimate of the Radius of the Exoplanet HD 149026b from Spitzer Photometry. *ApJ* **692** 1, 229–235

[75] Pasachoff J.M., Filippenko A. (2019, July 11): Final result of NameExoWorlds public vote. *The Cosmos: Astronomy in the New Millennium*, Cambridge University Press, 658—659. ISBN 978-1-108-43138-5

[76] Pearce T.D., Beust H., Faramaz V. et al. (2021): Fomalhaut b could be massive and sculpting the narrow, eccentric debris disc, if in mean-motion resonance with it. *MNRAS* **503** 4, 4767–4786

[77] Pepe F., Molaro P., Cristiani S., et al. (2014): ESPRESSO: The next European exoplanet hunter. *AN* **335** 1, 8–20

[78] Perryman M.A. (2000): Extra-solar planets. Rept. Prog. Phys. 63, 1209–1272

[79] PLATO Definition Study Report. ESA-SCI(2017)1, (April 2017) [online]. Retrieved 2022-05-16 from https://sci.esa.int/documents/33240/36096/1567260308850-PLATO_Definition_Study_Report_1_2.pdf

[80] PLATOSpec project web pages. (2020) [online]. Retrieved 2022-12-16 from https://stelweb.asu.cas.cz/plato/index.html

[81] Poddaný S., Brát L., Pejcha O. (2010): Exoplanet Transit Database. Reduction and processing of the photometric data of exoplanet transits. *New Astronomy* **15** 3, 297–301

[82] Podsiadlowski P. (1993): Planet formation scenarios. *Planets around pulsars*, Proceedings of the Conference, California Institute of Technology, Pasadena, April 30 – May 1, 1992 (A93-36426 14-90), 149–165

[83] Pultarova T. (2022, November 23): James Webb Space Telescope reveals alien planet's atmosphere like never before. [online] *space.com*. Retrieved 2022-12-20 from https://www.space.com/james-webb-space-telescope-details-exoplanet-atmosphere

[84] Ray A., Loeb A. (2017): Inferring the Composition of Super-Jupiter Mass Companions of Pulsars with Radio Line Spectroscopy. *ApJ* **836** 1, 135

[85] Ribas I., Tuomi M., Butler R.P. et al. (2018): A candidate super-Earth planet orbiting near the snow line of Barnard's star. *Nature* **563**, 365–368

[86] Richardson L.J, Deming D., Horning K. et al. (2007): A spectrum of an extrasolar planet. *Nature* **445** 7130, 892–895

[87] Ricker G.R., Winn J.N., Vanderspek R., et al. (2014): Transiting Exoplanet Survey Satellite (TESS). *JATIS*, Space Telescopes and Instrumentation 2014: Optical, Infrared, and Millimeter Wave

[88] Ricker G.R., Winn J.N., Vanderspek R., et al. (2015): The Transiting Exoplanet Survey Satellite. *JATIS* **1**(1), 014003

[89] Silvotti R., Schuh S., Janulis R., et al. (2007): A giant planet orbiting the extreme horizontal branch star V391 Pegasi. *Nature* **449**, pages 189–191

[90] Sing D.K., Fortney J.J., Nikolov N., et al. (2016): A continuum from clear to cloudy hot-Jupiter exoplanets without primordial water depletion. *Nature* **529**, 59–62

[91] Sinukoff E., Fulton B., Scuderi L. Gaidos E. (2013): Below One Earth: The Detection, Formation, and Properties of Subterrestrial Worlds. *Space Science Reviews* **180** 1–4, 71–99

[92] Šlechta M. (2020): Modernization of the 2m Perk telescope in Ondřejov *(available in Czech)*. *Astropis* **2020** 3, 12–15

[93] Šlechta M., Škoda P. (2002): 2-meter telescope devices: Coudé slit spectrograph and HEROS. *Publ. Astron. Ins. ASCR* **60**. 1–4

[94] Stellar Physics Department (2018), Ondrejov Perek 2m Telescope, [online] AI CAS. Retrieved 2019-04-24 from `https://stelweb.asu.cas.cz/web/index.php?pg=2m_telescope`

[95] Strickland A. (2017, June 19): NASA's Kepler mission finds 10 Earth-size exoplanets, 209 others. [online] *CNN*. Retrieved 2022-12-21 from `https://edition.cnn.com/2017/06/19/us/exoplanets-nasa-kepler-announcement/index.html`

[96] Struve O. (1952): Proposal for a project of high-precision stellar radial velocity work. *The Observatory* **72**, 199-200

[97] Šubjak J., Sharma R., Carmichael T.W. et al. (2020): TOI-503: The First Known Brown-dwarf Am-star Binary from the TESS Mission. *AJ* **159** 4, 151

[98] Suchan P. (2020, August 6): Český spektrograf bude lovit exoplanety. [online] Web pages of the Czech Astronomical Society. Retrieved 2022-12-16 from `https://www.astro.cz/clanky/exoplanety/cesky-spektrograf-bude-lovit-exoplanety.html`

[99] The JWST Transiting Exoplanet Community Early Release Science Team, Ahrer E.M, Alderson L. et al. (2022): Identification of carbon dioxide in an exoplanet atmosphere. Eprint arXiv:2208.11692

[100] The Science Week of the FNSPE CTU. [online]. Web pages of the Science Week, FNSPE CTU. Retrieved 2023-01-01 from `https://tydenvedy.fjfi.cvut.cz/`

[101] Tinetti G., Vidal-Madjar A., Liang M.C. et al. (2007): Water vapour in the atmosphere of a transiting extrasolar planet. *Nature* **448**, 169–171

[102] Triaud A.H.M.J. (2018): The Rossiter-McLaughlin Effect in Exoplanet Research; Handbook of Exoplanets, editors Deeg H., Belmonte J.A, *Springer International Publishing AG*, part of Springer Nature, id.2, ISBN 978-3-319-55332-0

[103] Trtíková I. (2019, May 14): PLATO – on the search for exoplanets with direct Czech participation. Retrieved 2022-12-16 from `https://www.vyzkumne-infrastruktury.cz/en/2019/05/plato-on-the-search-for-exoplanets-with-direct-czech-participation/`

[104] Trtíková I. (2019, November 28): Czech scientists will search for conditions for life on distant exoplanets with ESA's mission ARIEL. Retrieved 2022-12-16 from `https://www.vyzkumne-infrastruktury.cz/en/2019/11/czech-scientists-will-search-for-conditions-for-life-on-distant-exoplanets-with-esas-mission-ariel/`

[105] van Leeuwen F. (2007): Validation of the new Hipparcos reduction. *A& A* **474**, 653–664

[106] van Maanen A. (1917): Two Faint Stars With Large Proper Motion. *PASP* **29**, 258-259

[107] Veras D., Xu S., Rebassa-Mansergas A. (2018): The critical binary star separation for a planetary system origin of white dwarf pollution. *MNRAS* **473** 3, 2871–2880

[108] Wikipedia: ARIEL. In: *Wikipedia: the free encyclopedia* [online]. San Francisco (CA): Wikimedia Foundation. Retrieved 2022-11-23 from `https://en.wikipedia.org/wiki/ARIEL`

[109] Wikipedia: Barnard´s Star. In: *Wikipedia: the free encyclopedia* [online]. San Francisco (CA): Wikimedia Foundation. Retrieved 2022-11-23 from `https://en.wikipedia.org/wiki/Barnard%27s_Star`

[110] Wikipedia: Edwin Hubble. In: *Wikipedia: the free encyclopedia* [online]. San Francisco (CA): Wikimedia Foundation. Retrieved 2022-11-19 from `https://en.wikipedia.org/wiki/Edwin_Hubble`

[111] Wikipedia: Exoplanet. In: *Wikipedia: the free encyclopedia* [online]. San Francisco (CA): Wikimedia Foundation. Retrieved 2022-12-21 from `https://en.wikipedia.org/wiki/Exoplanet`

[112] Wikipedia: Giordano Bruno. In: *Wikipedia: the free encyclopedia* [online]. San Francisco (CA): Wikimedia Foundation. Retrieved 2022-11-18 from https://en.wikipedia.org/wiki/Giordano_Bruno#Cosmology

[113] Wikipedia: Kepler's laws of planetary motion. In: *Wikipedia: the free encyclopedia* [online]. San Francisco (CA): Wikimedia Foundation. Retrieved 2022-11-18 from https://en.wikipedia.org/wiki/Kepler%27s_laws_of_planetary_motion

[114] Wikipedia: List of highest-grossing films. In: *Wikipedia: the free encyclopedia* [online]. San Francisco (CA): Wikimedia Foundation. Retrieved 2022-11-17 from https://en.wikipedia.org/wiki/List_of_highest-grossing_films

[115] Wikipedia: Methods of detecting exoplanets. In: *Wikipedia: the free encyclopedia* [online]. San Francisco (CA): Wikimedia Foundation. Retrieved 2022-12-13 from https://en.wikipedia.org/wiki/Methods_of_detecting_exoplanets

[116] Wikipedia: Mount Wilson Observatory. In: *Wikipedia: the free encyclopedia* [online]. San Francisco (CA): Wikimedia Foundation. Retrieved 2022-11-19 from https://en.wikipedia.org/wiki/Mount_Wilson_Observatory

[117] Wikipedia: Thales of Miletus. In: *Wikipedia: the free encyclopedia* [online]. San Francisco (CA): Wikimedia Foundation. Retrieved 2022-11-18 from https://en.wikipedia.org/wiki/Thales_of_Miletus

[118] Wolszczan A. (1994): Confirmation of Earth-Mass Planets Orbiting the Millisecond Pulsar PSR 1257+12. *Science* **264**, 538–542

[119] Wolszczan A., Frail D.A. (1992): A Planetary System Around Millisecond Pulsar PSR 1257+12. *Nature* **355**, 145–147

[120] Žďárská J. (2021, January 31): Nadějný lovec exoplanet ARIEL: Na misi evropské sondy se podílí i čeští vědci. [online] 100+1. Retrieved 2022-12-16 from https://www.stoplusjednicka.cz/nadejny-lovec-exoplanet-ariel-na-misi-evropske-sondy-se-podili-i-cesti-vedci

[121] Zuckerman B. (2015): Recognition of the First Observational Evidence of an Extrasolar Planetary System. *PASP Conference Proceedings* 2015 **493** 291

[122] Zuckerman B., Koester D., Melis C. et al. (2007): The Chemical Composition of an Extrasolar Minor Planet. *ApJ* **671** 1, 872–877

# List of Figures

# List of Abbreviations

| | |
|---|---|
| AI CAS | Astronomical Institute of the Czech Academy of Sciences |
| AJ | The Astronomical Journal |
| ApJ | The Astrophysical Journal |
| ApJL | The Astrophysical Journal Letters |
| ARIEL | Atmospheric Remote-sensing Infrared Exoplanet Large-survey |
| AU | Astronomical unit (used as a standard distance unit) |
| A&A | Astronomy & Astrophysics |
| CCD | Charge-Coupled Device |
| CoRoT | Convection, Rotation and planetary Transits |
| DCR | Detect and Remove Cosmic Rays |
| ESA | European Space Agency |
| ESO | European Organisation for Astronomical Research in the Southern Hemisphere |
| ETD | Exoplanet Transit Database |
| FMP CU | Faculty of Mathematics and Physics of Charles University |
| FNSPE CTU | Faculty of Nuclear Sciences and Physical Engineering of Czech Technical University in Prague |
| FOV | Field Of View |
| IAU | The International Astronomical Union |
| IRAF | Image Reduction and Analysis Facility |
| JATIS | Journal of Astronomical Telescopes, Instruments and Systems |
| JBIS | Journal of the British Interplanetary Society |
| JWST | James Webb Space Telescope |
| ly | Light year (a distance unit) |
| $M_\oplus$ | Mass of the Earth (used as a standard unit) |
| $M_J$ | Mass of the planet Jupiter (used as a standard unit) |
| MNRAS | Monthly Notices of the Royal Astronomical Society |
| NOAO | National Optical Astronomy Observatory |
| OES | Ondřejov Echelle Spectrograph |
| PASP | Publications of the Astronomical Society of the Pacific |
| pc | A parsec (a distance unit) |
| PLATO | PLAnetary Transits and Oscillations of stars |
| PNAS | The Proceedings of the National Academy of Sciences |
| Res. Notes AAS | Research Notes of the American Astronomical Society |
| RM | Rossiter-McLaughlin effect |
| RV | Radial Velocity |
| SNR | Signal to noise ratio |
| TESS | Transiting Exoplanet Survey Satellite |
| ThAr | Thorium-Argon (lamp) |
| VLT | Very Large Telescope |

# A. Attachments

## A.1 The Science Week – Materials for students

### Calculation of the planetary mass from the radial velocities

A semi-major axis $r$ – a distance of the planet from the host star – can be calculated using Kepler's third law from the period of changes of the radial velocities $P_*$ as

$$r^3 = \frac{GM_*}{4\pi^2} P_*^2 \,, \tag{A.1}$$

where $G$ is the gravitational constant and $M_*$ is the mass of the host star (to find in the database). Using Newton's gravitational law we determine the planet's orbital velocity $V_\mathrm{p}$ (derived as the escape velocity from the surface of the star)

$$V_\mathrm{p} = \sqrt{\frac{GM_*}{r}} \,, \tag{A.2}$$

which we use to determine the mass of the exoplanet $M_\mathrm{p}$

$$M_\mathrm{p} = \frac{M_* V_*}{V_\mathrm{p}} \,. \tag{A.3}$$

The last parameter to find is the actual velocity of the host star $V_*$. Already determined Doppler (radial) velocity $K$ depends on the orbital inclination $i$ (the angle of the orbital plane of the planet). Inclination can be determined from transit photometry. Using the actual velocity of the star and the inclination of the exoplanet we can calculate the radial velocity as

$$K = V_* \sin(i) \,. \tag{A.4}$$

Source (online): Wikipedia: Doppler spectroscopy. Retrieved on January 1, 2023, from `https://en.wikipedia.org/wiki/Doppler_spectroscopy`.

## A.2 T-Excursion – Homework assignment

### The homework tasks

1. Search on the internet for the exoplanet discovered closest to the Solar system. How far away is it? How long does it take for the radio signal sent from the Earth to reach this exoplanet?

2. Before the observations, it is necessary to choose the targets (in our case the stars with the exoplanet candidates). How would you proceed when selecting the targets? What criteria would you use for the selection of stars for observation on a particular night? Try to describe the most important parameters. A useful hint – they can be the stellar characteristics or the observational and weather conditions.

3. The search for extraterrestrial life is one of the main reasons why we study exoplanets. What should be the ideal characteristics of an exoplanet to have the conditions suitable for life? What should be the exoplanets scientists should look for when searching for life on them? Think about the parameters determining the possibility of the existence of life.

## A.3 T-Excursion – Practical assignment

### Tasks for the practical part

For the practical part of the T-Excursion, you will get a figure of the light curve of transit observation of the exoplanet. Your task is to determine some of the basic information about the examined exoplanet.

Look at the light curve of the WASP-36 transit in figure A.1 indicating a possible presence of the exoplanet. Use the figure of the transit to determine the following:

1. How long was the duration of WASP-36 transit (expressed in hours)?
2. What is the maximum decrease in stellar brightness during transit?
3. Can we observe the limb darkening during the given transit? What would the light curve look like with no limb darkening?
4. We know the diameter of WASP-36 is $R_* = 0.943$ of the Solar radius. Using the formula for the ratio of the squares of stellar and planetary radii (written in the study materials, in this thesis it is formula 2.3) calculate the diameter of the exoplanet $R_\mathrm{p}$. Write the result in kilometres and round it to 3 significant digits.
5. Let's assume the star WASP-36 has the same mass as our Sun. The transit period on the examined exoplanet is 1.54 days. Determine the distance of this planet from the star (i.e. the semi-major axis). Write the result in kilometres and round it to 3 significant digits.
6. Let's assume WASP-36 has most of the characteristics similar to the Sun (e.g. mass, radius, surface temperature, luminosity etc.). In that case, is the examined exoplanet located in the habitable zone of the star?
7. What is the distance of WASP-36 from the Solar system?

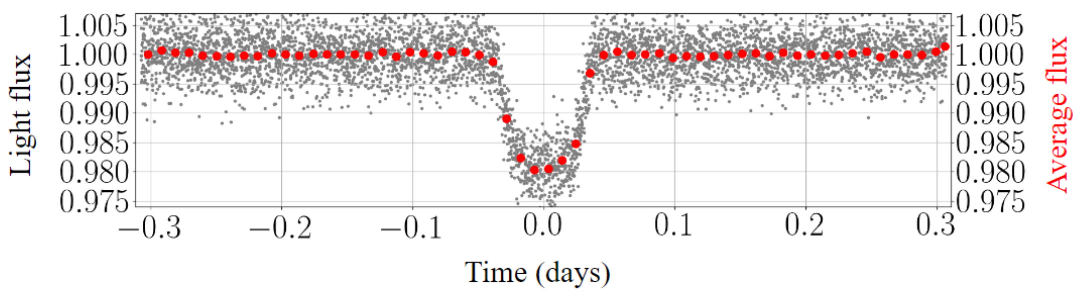


Figure A.1: Light curve of the transit observation of WASP-36.

## A.4 Data processing pipeline – Example script

### Script 3_Image_Reduce_1.cl for basic spectra reduction

```
# edited or reviewed on 2022-04-21
# added the package names before the cosmicrays task (the task was not
   working without it)

print "============ Bad pixels correction ....... fixpix ============"
fixpix images=@All_frames.list masks=badpixmask verbose=yes

print "========== Cosmic rays correction ...... cosmicrays =========="
noao
imred
crutil
cosmicrays input=@frames.list output=@frames.list fluxrat=10 window=7
   interac=no answer=yes
bye

print "======== Cut outer regions of the image ....... imcopy ======="
imcopy *fit[5:2039,500:1749] *fit

print "=========== Create master bias ....... zerocombine ==========="
zerocombine input=@bias.list output=mbias combine=median ccdtype=" "
   nlow=2 nhigh=2 nkeep=0 rdnoise=10 gain=2

print "===== Subtract master bias from flat images ... imarith ====="
imarith operand1=@flat.list op=- operand2=mbias result=@b_flat.list

print "=========== Create master flat ....... flatcombine ==========="
flatcombine input=@b_flat.list output=mflat combine=median reject=
   sigclip ccdtype=" " process=no subsets=no scale=none nlow=2
nhigh=2 rdnoise=10 gain=2

print "mbias ... done"
print "mflat ... done"
print "============ Script Image_Reduce_1.cl ....... done ==========="
```

## A.5 Data processing pipeline – Manual

Version 2023-01-05 22:02

### 1. Installation and setting up IRAF and other software

#### Installing IRAF

Download IRAF from `https://github.com/iraf-community/iraf/blob/v2.17/INSTALL.md` and proceed as the instructions say to successfully install it. Since Ubuntu 20 it is also possible to install IRAF directly from the Ubuntu software centre.

#### Launching IRAF

After the first initial `mkiraf` command login.cl file and uparm directory should be created at the home (or root) directory. Now you just need to open the terminal for IRAF (I suggest xgterm, see below for more information on how to set it up and use it). In the terminal then run command `ecl` to start the IRAF (also the command `cl` works but you might have problems with the controls - for example arrows and backspace do not work – command `ecl` should fix these issues and if not, it is possible to use `irafcl` command).

#### Setting up login.cl file

A file named login.cl contains the basic IRAF setup. After the first `mkiraf` command you need to find the login.cl file, which we will edit to set up the several parameters or packages necessary for work with IRAF. If you need to set up the file permissions to write to the document and save it, the following command might do the trick:

```
sudo chmod -R 777 login.cl
```

IRAF can create several login.cl files and it might be safe to edit all of them. To the set up of login.cl file, we add the following packages: `noao`, `imred`, `ccdred`, `echelle`, `rv`. These packages are used for data processing and loading them in login.cl file means we do not need to do this again every time we start IRAF. To add the packages write the following parameter and packages before the last line (containing `keep`):

```
set fkinit='noappend'
noao
imred
ccdred
echelle
rv
```

Description of the main packages:

- `noao` - the basic package for the data reduction containing other packages
- `imred` - used for the basic image reduction (flat field correction, dark frame correction, zero corrections etc.)

- `ccdred` - again one of the basic packages for processing the CCD camera images
- `echelle` - package for the processing of the echelle spectra, it contains tasks for rectification and normalisation of the echelle spectra
- `rv` - package necessary to determine the radial velocities of the star displayed in the spectra

Then we can modify two parameters useful for the work with IRAF. The first one helps with opening the images on full screen. Thanks to the second one we do not need to use the file suffix to open spectra. To set both, we just change the following parameters in the lines (both are located almost at the top of the login.cl file):

```
#set    stdimage      = imt4096
#set    imtype        = "fits"
```

### Add the observatory to the database

Adding the observatory means writing the necessary geographical parameters of the observatory where the spectra were taken to the IRAF library, so it could be used during the data reduction (for example the exact location is necessary for heliocentric correction to get the precise results of the radial velocities). Locate the file obsdb.dat which works as a database of the observatories and their basic information and then add to the end of the file these lines (you may need to change the permissions to edit the file):

```
# Submitted by Marek Skarka 7/12/17
observatory = "ONDREJOV"
       name = "Ondrejov, Czech Republic"
       longitude = -14:47:01
       latitude = 49:54:38.0
       altitude = 528
       timezone = -1
```

### Add the catalogue for wavelength calibration

You need to find the location of the linelists directory (for my system its location is `home/daniel/iraf-2.17/noao/lib/linelist`). Then just add the thar_new.dat file from the received workshop directory there (the change of permissions may be necessary).

### Installing xgterm

If there is a problem with missing xgterm which was not installed with the IRAF, you can download and install the package x11iraf-2.1 containing xgterm. Download it from `https://iraf-community.github.io/x11iraf.html` and follow the instructions for installation. However, do not install IRAF like it is written in the system requirements (do not execute the command `sudo apt install iraf-dev`), since you have already installed IRAF (it would install another version of it).

### Setting up xgterm

At home directory find the file .bashrc and write at the end of the section `# some more ls aliases`

```
alias myterm='xgterm -sb -fg "white" -bg "black" -cr green'
```

It will set up a better setting of xgterm used for work with the IRAF software (of course the colours are up to you). To apply the changes use the command

```
source ~/.bashrc
```

After this you can run your xgterm simply with the command (the terminal will run until you close the xgterm):

```
myterm
```

### Installing Sao Image DS9

To view the echelle spectra and all the images we are working with, we need the DS9 software. To download it, go to `https://sites.google.com/cfa.harvard.edu/saoimageds9` and follow the instructions at `https://www.iiap.res.in/files/DS9-Ubuntu_0.pdf`. After the installation, you can run DS9 from the command line with the command

```
ds9
```

It is possible to install the DS9 directly from the Ubuntu software centre.

### Setting up DCR

DCR (Detect and Remove Cosmic Rays) will help us with the data reduction – the reduction of cosmic rays. Download it from `https://users.camk.edu.pl/pych/DCR/`. I suggest following the instructions for installation of the DCR binary[1].

## 2. Basic Information to the OES Data

All the raw data from OES (Ondřejov Echelle Spectrograph) are in .fit format. From every night, we get the object spectra and several types of correction images.

The object spectra are located in directory "object" separately - each object is in its own directory. To process the data, we need to put the files into the main "object" directory. Later we also write the object's name to the script `1_Vytvor_Seznamy.sh`.

In directory "zero" there are bias images (also called zero images). These correction images are taken with zero exposition time. They are used to reduce the read out noise.

Flat lamp images (stored in directory "flat") are used to correct the optical defects on the optical path from the entry point into the telescope down to the camera. We use the so-called lamp flats which are taken using an internal calibration lamp.

[1] `https://soardocs.readthedocs.io/projects/goodman-pipeline/en/latest/_install_dcr.html`

Comparative images, also called arc images are located in “comp” directory. These are the spectra of the Thorium-Argon lamp (ThAr lamp) and they are used for calibration of the wavelengths for the object spectra. For the spectra calibration we use just the last comp image from the observation (from the end of the night) and we delete the others. The comp.list will contain just this one file on it.

## Basic IRAF commands and tasks

Basic bash commands work in IRAF:

| | |
|---|---|
| pw | to find the current path |
| ls | list all the object in directory |
| ls -l | detailed list of all the objects in directory |
| cd /<path>/ | change directory |
| cd | exit directory |

To use some task, just write the task and its main parameters (e.g. input, output or other parameters): <task> <parameters>.

You can also set the parameters using epar task:

| | |
|---|---|
| epar <task> | settings parameters of the task |
| :go | run the task |
| :q | save settings and exit the task setup |
| :q! | exit task setup without saving it |
| " " | to leave the parameter empty, write just an empty space |
| @list | to use the list of object, write @ in front of its name |

Using packages:

| | |
|---|---|
| <package> | use the package |
| bye | exit the previously called package |

## 4. Step-by-step tutorial

This part of the manual is based on Dr. Marek Skarka’s tutorial. We will use the data from August 7, 2020. The target object is TYC 1083-12-1 and for the aperture templates, we will use the Vega spectrum from the same night.

At first, we prepare our dataset for data processing. We add the script 1_Vytvor_Seznamy.sh to the main directory alongside the object, flat, comp and zero images directories. Then we write to the script the path to this directory and the name of the object we are going to process. We write there also the path to the scripts, which are stored in one separate directory. At last, we delete all the comp images except the last one (we need the ThAr lamp to warm up first to stabilize itself).

**Step 1:** Run the first script (1) in a bash terminal.

```
sh 1_Vytvor_Seznamy.sh
```

The script does the following:
- creates a special working directory
- makes a list of bias images
- makes a list of flat images
- makes a list of comp images
- makes a list of object images
- moves all the images and lists to the working directory
- moves all the necessary scripts to the working directory

For testing purposes all the object images were named Test in the script, the first one is Vega, and the second one is TYC 1083-12-1.

The first step of the data reduction is to clear the data from the cosmic ray peaks - all images except the comp spectra (frames.list).

**Step 2:** Move to the working directory `/pracovni/`.

```
cd pracovni
```

and run the second shell script (2)

```
sh 2_Cosmic_Remove.sh
```

The script uses the software DCR to remove cosmic ray from the spectra. We use two different procedures as they are more effective when combined. The second procedure will be used as part of the next script.

**Step 3:** Run from IRAF terminal the third script (3).

```
cl < 3_Image_Reduce_1.cl
```

The script does the following:
- makes correction of the bad pixels
- runs task cosmicrays to remove the cosmic ray
- cuts away specific regions of all the images
- creates master bias image (called mbias)
- subtracts master bias from flat images
- creates master flat image (called mflat)

We cut away outside parts of the image to eliminate the borders of the spectra, which are usually flawed. Flat fields calibrated with master bias are named with prefix "`b_`".

The next step is to create an aperture template to identify the apertures at all the object spectra. We use a new aperture template for each night or at least for no more than 2 weeks. Usually, bright stars are used (we will use the spectrum of Vega) If we already have the aperture template ready, we skip the next step and move to the next script (5).

**Step 4:** Change the name of the aperture template (to `aper_temp_1`) in the script (4) and run it.

```
cl < 4\_Aper\_Template\_Create.cl
```

We confirm default options (enter). A graphic window shows up (warning: do not close it another way than finishing the process – it won't work and you will have to restart IRAF).

There are several controls in the newly opened graphic window:

| | |
|---|---|
| `w + e+e` | zoom in to particular part of the spectrum (defined as rectangle with cursor and keys "`e`") |
| `w + a` | show all (zoom out) |
| `d` | delete aperture |
| `m` | define new aperture |
| `q` | continue or quit (only after you are finished) |

We delete all apertures which are found automatically (just point to the peak and press `d`) and then we define the new apertures (again just point to the peak and press `m`, IRAF will centre the aperture automatically). As default there are 56 apertures, however, we will use only 40 which are located between the wavelengths from 4000 A to 7300 A. We start with the first aperture identified as the one on the left before the first (small) decrease of peak height between otherwise rising heights, the second (quite significant) decrease being 5 peaks away on the right. On the x-axis, the first identified peak should match approximately pixel 410.

When finished, press `q` and choose "yes" (enter) three times, so we can trace the apertures interactively. As a default, we see the traced aperture, but the tracing is more precise when we look at residuals (relative or absolute values). There we can delete bad pixels and re-fit the aperture.

We can use the following controls:

| | |
|---|---|
| `j` | show residuals in the relative pixels |
| `k` | show residuals in the absolute values |
| `h` | back to the overview of the aperture |
| `:o 10` | change the order of the fit to value 10 |
| `f` | re-fit the aperture (after changing the order etc.) |
| `d` | when moving to pixel – remove pixel from fitting (need to re-fit) |
| `q` | (and confirm yes) – move to the next aperture |

When we are on a level of about $\pm 1/100$ of the pixel (in relative pixels), it is a good fit.

The apertures should be defined in order so the big absorption line is located on the second aperture and the H-alpha line is on the 35th aperture (this applies specifically for Vega or A-type stars, for other stars it varies).

After going through all the apertures, we confirm with "yes" and then we extract the apertures from the spectrum by confirming "yes" again. In the working directory, a new image with extracted apertures is automatically created called `aper_temp_1.ec.fits` which will be later used as the template for apertures (so we do not need to extract them on all the images) and also two files in database directory (`apaper_temp_1` and aplast) containing information about the extracted apertures.

We can review the extracted apertures:

```
splot aper_temp_1.ec
```

and then confirm "yes" (enter) to continue with the first aperture. Controls:

| | |
|---|---|
| `)` | move to the next aperture |
| `(` | move to the previous aperture |
| `q` | quit the graphic mode |

Attention – if you close the window without the command `q`, IRAF will crash!

When you are working with the data from more nights (just a few days apart at maximum), do not forget to save the `aper_temp_1` and its database files for the next use.

In the next step, we will create a normalized master flat (called nflat) from the master flat image created using the script (3).

**Step 5:** Run the script (5).

```
cl < 5_Apflatten_Script.cl
```

We confirm recentering the apertures for flat (yes), and then we can see all 40 apertures were shifted by 0.32 pixels (or a similar amount) for flat. We confirm editing apertures for flat (yes).

In the graphic window, at first, we recenter the apertures. We can do it one by one – moving the cursor to the aperture and pressing `c` (for automatic recentering) or `g` (for automatic gauss fit) – both options work pretty much the same and it is not important which one we choose. We can also recenter all the apertures at once – press `a` and then `c` or `g`.

We move to the next step, by pressing `q` and confirming all the options. As the next step we will fit the apertures of the flat – we can see the intensity on the y-axis of the figure now. We watch the RMS – e.g. RMS value 4.602 when the intensity is up to 400 for the selected aperture is good (so 4.6/400 is good).

The same controls work here as before (`j, k, h, d, :o 10, f, q`...). The pixels in the diamond are ignored. Later, especially on the edge of the apertures, the fitting is not working very well. We can set higher order (e.g. 15) and re-fit the aperture (do not forget), but it won't change much. We cannot do more about it.

After we finish all the apertures, they are extracted into the normalized master flat. Another file called apmflat was created in the database directory.

Now we can continue with the data reduction using the next script.

**Step 6:** Run the script (6).

```
cl < 6_Image_Reduce_2.cl
```

The script uses task imarith to do several operations:
- subtracts master bias from comp image
- divides comp image reduced of bias by normalized master flat
- subtracts master bias from object images
- divides object images reduced of bias by normalized master flat

Next, we will continue with the object spectra extraction.

**Step 7:** Run the script (7).

```
cl < 7_Spectra_Extract.cl
```

The script works with the appal task. We will extract the spectra of object images. For that, we already have the aperture template prepared, we just have to edit its name in the script (update the number of the template).

When running the script, we confirm recentering apertures (yes) and editing apertures (yes). In a graphic window, we use again the same controls as before to recentre the apertures (`a, c, g`. If the apertures look good (they should, especially for the Vega image, which is used as the template), we press `q`, confirm writing to the database (yes) and aperture extraction (yes). Then we proceed to the next image – again confirm recentering (yes) and editing (yes).

To review the extracted spectra (not always necessary):

```
splot bf_ec202008070038.ec
```

We can see several bad pixels or cosmic ray peaks (for example in the test data it is the aperture number 13 or 25 – the peaks are too narrow to be the spectral emission lines). At the aperture number 35, we can see an H alpha spectral line (in this case it is split in two – possible stellar binary system). At the aperture of 37, we see the telluric lines (from the Earth's atmosphere).

Until now, all the spectra were displayed in pixels on the x-axis. We need to change that so the nanometres (or angstroms) are on the x-axis. For this wavelength calibration, we use comp image – a spectrum of the Thorium-Argon lamp, where we identify the well-known spectral lines – and then compare it to the object spectra.

In the next step, we edit the object spectra (in the database file). Effectively we change the width of the spectra aperture which we will use for the wavelength calibration. However, this is helpful only for the bright stars (as the one used for testing), where we have a high SNR. For the faint stars, it would not be possible to use. Therefore, the next two steps are quite specific for our testing data and the process would be slightly different for other stars.

**Step 8:** Run the script (8).

```
sh 8_Zmensi_Aperturu.sh
```

Then we continue with extracting the comp spectra. The process is similar the object image extraction.

As the next step, we have to manually edit the script (9). To do that, we open the script and rewrite the values of the following parameters:

| | |
|---|---|
| `input=` | we use the comp name from `bf_comp.list` (e.g. `bf_e202008070051` – we use it with prefix "`bf_`" but without suffix "`.fits`") |
| `referen=` | we use the name of the first object from `bf_obj.list` (write it the same way as comp name) |
| `output=XXcomp.ec` | where `XX` stand for last two digits of the first object name written in the parameter `referen` |

Now we copy the whole task under the first one and do the same rewriting for all objects from the `bf_obj.list`. We always change only parameters `referen=` and `output=`, the `input=` parameter stays the same for all the images from this night.

In the end, we have as many apall task lines in the script as the objects in `bf_obj.list`. After we save the script, we can run it.

**Step 9:** Run the script (9).

```
cl < 9_Comp_Extract.cl
```

Now we will manually make a backup of our working directory. We just copy the directory and rename it to `pracovni_backup_1`.