CHARLES UNIVERSITY IN PRAGUE

FACULTY OF MATHEMATICS AND PHYSICS

DIPLOMA THESIS

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Spectroscopic study of the star 70 Virginis and its planetary system

Astronomical Institute of Charles University

Supervisor: prof. RNDr. Petr Harmanec, DSc.
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V Praze dne 10.8. 2007 Václav Klusák

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Abstrakt

Název práce: Spektroskopická studie hvězdy 70 Virginis a jejího planetárního systému

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Abstrakt: Soudobé znalosti o exoplanetách byly shrnuty a termilogie diskutována. Jádrem práce byla 'metodologická studie'. Na základě spekter z DAO, Kanada, dvě větve řešení byly vyzkoušeny a porovnány. Za prvé, programem SPEFO byly změřeny metalické čáry. Za druhé, spektra byla rozmotána KORELem a změřena ve SPEFU.

Tento rámec a technika rozmotávání spekter mohou být využity pro studium exoplanet. Avšak, zabezpečení výrazně většího souboru vstupních spekter je nezbytné.

The second branch included the merging of DAO spectra with spectra provided by Naef & al. **Klíčová slova:** extrasolární planety, 70 Vir, radiální rychlosti, metody zpracování spekter

Abstract

Title: Spectroscopic study of the star 70 Virginis and its planetary system

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Abstract: The contemporaneous knowledge of exoplanet research was resumed and terminology discussed. The core of this diploma thesis was 'the methodology study'. Using the set of spectra taken at DAO, Canada, two branches solution were tested and compared. Firstly, metallic lines of DAO spectra were measured using SPEFO. Secondly, the spectra were disentangled using KOREL and measured using SPEFO.

The fundamental question was if this data analyzing framework (SPEFO, FOTEL) and the disentangling technique can be used for exoplanet research.The answer is confirmative, but the need to base analysis on a significantly bigger set of spectra to get more accurate results appeared.

Keywords: extra-solar planets, 70 Vir, radial velocities, methods of spectra analysis

Introduction

Motivation

The past two decades witnessed a great deal of effort and many resulting spectacular achievements in the extra-solar planets research. While in the middle of 1980's there were no extra-solar planets proved to be, nowadays (according to [16] The Extrasolar Planets Encyclopedia) more than 240 planets within about 210 star systems are known.

This research deals with essential questions of the planetary systems formation. Furthermore, the research is important for the questions of the origin of life and the existence extra-terrestrial life. Therefore the discovery of extra-solar planets may be viewed as a subject of interest of both the public and the media.

Further extra-solar planets research techniques are discussed, new ground projects launched and new related space satellites projected. Regarding the dynamicity of the extra-solar planets field, a great farther development may be expected in the near future.

On the other hand, this development brings several questions to be discussed. Among others, the demand to test continuously reachable limits of the detection threshold may appear. And it ought to be noticed that the detection threshold is not only set by 'hardware', by technical limits of telescopes, detectors etc., but it might by strongly effected by 'software', by the data analyzing procedures.

Further, the demand to summarize continuously new knowledge in the expanding field of the extra-solar planets research may appear. Regarding a number of different projects and scientific teams acting in the field nowadays, it may be necessary to summarize both general extra-planets knowledge and pieces of information related to particular extra-planetary systems. Yet, because of the similar reasons, a need to keep a common precise terminology and to set continuously new exact definitions may appear. Concerning the fact that the official IAU's definition of a planet refers to the Solar System only, and dealing with various kinds of the sub-stellar objects, a reconsideration of the definition of a planet seems to be inevitable in the near future.

The outline of the diploma thesis

Considering what was explained above, the goals of this diploma thesis are formulated.

The first task is to critically discuss the terminology used in connection with extra-solar planets and to suggest the working definitions to be used thereafter.

The second task is to critically discuss the contemporaneous general knowledge in the extra-solar planets research.

The third part of the thesis is devoted to the well-known extra-solar planet system around a late-type star 70 Virginis (hereinafter '70 Vir'). The independent determination of orbital parameters of the system 70 Vir should be the central task of the diploma thesis. The determination will be based on spectra obtained in Dominion Astrophysical Observatory in Canada. Different data analysing processes will be tested and compared.

Chapter 1

Knowledge résumé

1.1 History and terminology

1.1.1 History of extra-solar planets research

Concerning both the terminology and the existing knowledge of extra-solar planets, it must be underlined that reliable observations of extra-solar planets are available for a few years only.

Indeed, an ancient tradition of extra-solar planets intellection can be described. Among others, let us mention thinking of philosophers Epikuros ($4^{th}/3^{rd}$ century B.C.) and Giordano Bruno (16^{th} century) and a serious observational attempt of Christian Huygens (17^{th} century). Several unconvincing observations appeared in the second half of 20^{th} century; e.g. Barnard's star (GJ 699) and β Pictoris.

Both of these stars remain a challenging question until now. Barnard's star is one of the nearest stars[1] to the Sun (1.82 pc).[2] β Pictoris seems to be a very young star ($8-20$ million years)[3], surrounded with a cloud of dust and gas (a debris disk). The first studies of the system were launched with IRAS program observations and ground observations (e.g. at the observatory Las Campanas in Chile)[4]. Since that, the presence of planets (of Jovian or

[1] Following [35] Küerster & al. (2003).

[2] A discovery of two Jovian planets was announced by Peter van de Kamp in 1960's (see e.g. [33] van de Kamp 1982). Although the measurements were not proved and quite strict limits of the planets exclusion were recently settled (approx. $m.sin(i) = 0.12M_J$ – see [35] Küerster & al. 2003), Barnard's star was chosen as a substantial target for NASA Space Interferometry Mission and for ESA Darwin project.

[3] Following a general overview at [62]; in [8] Chen & al. (2007) is the age estimated at approx. 12 million years.

[4] See [60] Smith & Terrile (1984) and [27] Hobbs & al. (1985).

terrestrial sizes) was suggested ([19] Gorkavyi & al. 2000) based on the analysis of the disk structure.

Recently, a group led by Y. Okamoto and a group led by H. Chen discussed the presence of small bodies (asteroids, comets) within the system – see [8] Chen & al. (2007). It seems that a process of planetary formation is still going on in the β Pictoris system, or that it has ended quite a short time ago. And regarding the possibility of the presence of several types of sub-stellar bodies, β Pictoris remains therefore a very promising target even after 25 years of studies.

The very first convincing observations of extra-solar planets came only in 1990's. Three planets were discovered within the system of the pulsar 1257+12 in 1991 (see [76] Wolszczan & Frail 1992). And later on, the first extra-solar planet orbiting a main sequence star, 51 Pegasi, was discovered in 1995 (see [43] Mayor & Queloz1995).

1.1.2 Terminology

There may be seen similarities between history of terminology of the Solar System bodies and evolution of terminology of extra-solar planets. Because of the discovery of new objects (Ceres, Vesta etc.), a new category (in addition to 'planets') of asteroids was established later. Further, terminology started to distinguish between terrestrial and Jovian types of planets. And finally, based upon the increasing number of relatively huge trans-Neptunian objects, a class of 'dwarf planets' was settled.

The present day terminological frame of the Solar System bodies was formulated during the 26th General Assembly of International Astronomical Union (further on 'IAU') in Prague in August 2006.

> **"RESOLUTION 5A**[5]
>
> The IAU therefore resolves that 'planets' and other bodies in our Solar System, except satellites, be defined into three distinct categories in the following way:
>
> (1) A 'planet' is a celestial body that (a) is in orbit around the Sun, (b) has sufficient mass for its self-gravity to overcome rigid body forces so that it assumes a hydrostatic equilibrium (nearly round) shape, and (c) has cleared the neighbourhood around its orbit.

[5] According to [64] Webpages of IAU.

> (2) A 'dwarf planet' is a celestial body that (a) is in orbit around the Sun, (b) has sufficient mass for its self-gravity to overcome rigid body forces so that it assumes a hydrostatic equilibrium (nearly round) shape, (c) has not cleared the neighbourhood around its orbit, and (d) is not a satellite.
>
> (3) All other objects except satellites orbiting the Sun shall be referred to collectively as 'Small Solar-System Bodies'."

Let us notice that this definition is 'valid' for the Solar System objects only.

One of the greatest surprises, which have been brought with the extra-solar planets discoveries in the past two decades, is definitely the diversity of sub-stellar objects. Regarding mass, orbital parameters, density, chemical composition, surface conditions and (probably) processes of formation there are several classes of objects, which are not represented in our Solar System. Moreover, regarding the increasing number of extra-solar planets and growing of knowledge, it seems unlikely there are sharp borders among object classes. E.g. we may refer about the border of planets and brown dwarf as "the semantically nebulous gray area" (Marcy, Butler); contrasting to a very sharp and concise distinction between terrestrial and Jovian planets of the Solar System.

Sometimes, one may even be witnessing some hesitations in the usage of the term 'planet' for extra-solar objects at all:

> *"For the reason above, it is tempting to classify 47 UMa B as a giant 'planet'. We caution that the term 'planet' is loaded with implication steaming from the nature and supposed formation of the planets in our solar system."*[6]

Furthermore, in order to properly describe newly discovered characteristics of extra-solar planets, authors keep introducing new terms; e.g. 'eccentric planet', 'extra-solar Saturn', 'hot Neptune' etc. Therefore a certain level of disturbance might be seen in extra-solar planets terminology. Hereat working definitions will be settled for the purposes of this diploma thesis.

IAU's Working Group on Extra-Solar Planets (further 'WGESP'[7]) was established in 2000. In August 2006 WGESP was transformed into IAU Commission 53 (a part of Division III)[8]. WGESP created a working definition of extra-solar planets.

[6] According to [6] Butler & Marcy (1996), page L156.

[7] Group de travail sur les planètes extra-solaires. See [73] Webpages of WGESP.

[8] The commission president is M. Mayor, the vice-president is A. Boss.

Firstly, WGESP states that *"rather than try to construct a detailed definition of a planet which is designed to cover all future possibilities, the WGESP has agreed to restrict itself to developing a working definition applicable to the cases where there already are claimed detections?"*[9]. Definitely, this "gradualist approach with an evolving definition" is very suitable for the field of extra-solar planets, as the knowledge basis keeps expanding rapidly nowadays. WGESP has agreed then:

> "(1) Objects with true masses below the limiting mass for thermonuclear fusion of deuterium (currently calculated to be 13 Jupiter masses for objects of solar metallicity) that orbit stars or stellar remnantswebpages are 'planets' (no matter how they formed). The minimum mass/size required for an extrasolar object to be considered a planet should be the same as that used in our Solar System.
>
> (2) Substellar objects with true masses above the limiting mass for thermonuclear fusion of deuterium are 'brown dwarfs', no matter how they formed nor where they are located.
>
> (3) Free-floating objects in young star clusters with masses below the limiting mass for thermonuclear fusion of deuterium are not 'planets', but are 'sub-brown dwarfs' (or whatever name is most appropriate)."

Concerning the 1^{st} paragraph of the definition, although the definition was created before the adoption of the Resolution on planets of the Solar System (see hereinabove), it can be easily connected with the definition of the Solar System planets.

There are suggestions within a general discussion on extra-solar planets that a term planet should be limited to objects orbiting stars (i.e. stars giving thermonuclear fusion inside). That would exclude namely the objects orbiting pulsars[10]. As such an approach seems to be too restrictive and quite far from the standard practice[11], let us follow the WGESP definition and consider the term 'planet' in a broader way.

Regarding the IAU Resolution on the Solar System planets, the WGESP proposal should be amended with definitions of (extra-solar) dwarf planets and of small bodies (of an extra-solar system). That is not needless

[9] According to [73] Webpages of WGESP.

[10] E.g. the very first extra-solar planets at the system of pulsar 1257+12; see hereinabove.

[11] The pulsar orbiting objects are for example enlisted in [16] The Extrasolar Planets Encyclopedia as extra-solar planets.

pedantry – the question of subplanetary objects in extra-solar systems is topical (e.g. β Pictoris, see hereinafter).

Regarding the free-floating objects, the term 'sub-brown dwarf' seems to be quite an unnatural. We should consider a cultural background – for free floating objects of planetary sizes a term planet is traditionally used, namely in imaginative literature.

To conclude, let us settle the working definitions on planets and other objects:

Sub-stellar object – is an object with mass smaller than is necessary to maintain hydrogen thermonuclear fusion[12]. Excluding all substantial stellar remnants - white dwarfs, neutron stars and black holes. Sub-stellar objects may be divided into four groups: brown dwarfs, planets, dwarf planets and small bodies.

Low-mass companion – is a sub-stellar object orbiting a star.

Brown dwarf – following WGESP definition it is a sub-stellar object with mass above the limiting mass for deuterium thermonuclear fusion; no matter how it is formed, nor where it is located.

Planet, dwarf planets and small bodies – follow the IAU Resolution on the Solar System planets, but generally no matter where they are located. Based on the location, planets, dwarf planets and small bodies may be distinguished into objects of our Solar System and extra-solar objects[13]. Extra-solar objects then into objects orbiting other stars and interstellar objects[14].

Without prejudice to these working definitions let us briefly observe other criteria of the distinction of these objects. The lithium test (R. Rebolo) should be mentioned regarding the distinction between small stars and brown dwarfs. The presence of methane in the atmosphere could be another clue to distinguish a brown dwarf.

G. Marcy and R. Butler refer to the distinction between brown dwarfs and planets:

> *"Brown dwarfs are thought to differ from planets in that they form by gravitational collapse (as do stars) while planets are built up by dust accretion in the disk of a protostar, followed by hydrodynamic acquisition of gas (Boss 1986; Lissauer 1995)*[15]*. Phys-*

[12] Approx. $80M_j$.

[13] Shortly 'exoplanets', 'dwarf exoplanets'.

[14] E.g. an interstellar planet, i.e. a free-floating planet (a planetar).

[15] See [4] Boss (1986) and [39] Lissauer (1995).

ically, giant planets supposedly differ from brown dwarfs in that they have a rocky core of 10 Earth masses. There is currently no observational means of determining the core composition of substellar objects, but the energy generation from deuterium burning in brown dwarfs may be inferred (Saumon, Burrows & Hubbard 1995)[16]*.*"[17]

1.2 Extra-solar planets research

1.2.1 Planetary formation

The today's mostly respected theory of planets formation[18] presents an elaboration of the concept of P.-S. de Laplace. Planets (and stars) are thought to be formed from fragments of interstellar nebulae. After a gravitational formation of a protostar in a center of a fragment, dust and ice particles gather into small metre bodies in a disk surrounding the protostar. By the accretion the planetesimals ([67] Safronov 1969) and later the protoplanets are formed. The protoplanets farther from the star may attract certain amount of gas. Therefore, the planets closer to the star remain rocky ones (terrestrial type), farther planets could become gas giants (Jovian type).

However, many giant gas extra-solar planets were discovered too close to a parent star (e.i. orbital radius of 0.1 AU for example). It is obvious that the classical theory of planets formation must be amended; most probably with specific models of planet migration. It is believed that Jupiter-mass planets are formed at large distance from their parent stars and some fraction then migrates in (see [77] Wu & al. 2007).

More details about planets formation can be found e.g. in [39] Lissauer (1995); [3] Bodenheimer & al. (2000) and [50] Raymond & al. (2005). [64] Tsukamoto & Makino (2007) shows the possibilities of planet formation in the binary systems. Results of simulation of terrestrial planet formation at low-mass stars can be found in [51] Raymond & al. (2007). Recent details on planetary migration can be found in [47] Pierens & Nelson (2007); [1] Armitage (2007), or in [63] Teroquem & Papaloizou (2007).

[16] See [55] Saumon & al. (1995).

[17] According to [42] Marcy & Butler (1996).

[18] With regard to general overviews in [29], [45],[34] and [74].

1.2.2 Methods of extra-solar planets detection

Radial velocity

In light of a number of detected exoplanets, the most important method is the measurement of radial velocities through changes of a stellar spectrum. As a star (orbited with a planet) moves in a direction towards/onwards an observer (with ‘radial velocity’), because of Doppler effect the shift of stellar spectral lines can be observed and the radial velocity curve can be derived.

It must be underlined that it is not possible to measure the mass of the planet M_P itself, when the geometry of the system is unknown. However, the inferior mass limit $M_P \sin i$ can be determined, where i is the inclination of the orbit of the planet[19]. Concerning the amplitude of radial velocity curve K; orbital period P; the eccentricity of the orbit e; mass of the star M_*; then

$$K = \left(\frac{2\pi G}{P}\right)^{1/3} \frac{M_P \sin i}{(M_P + M_*)^{2/3}} \frac{1}{(1-e^2)^{1/2}} \tag{1.1}$$

Approaching the orbit with a circle and concerning $M_P \ll M_*$, then

$$K = 28.4 \left(\frac{P}{1yr}\right)^{-1/3} \left(\frac{M_P \sin i}{M_J}\right) \left(\frac{M_*}{M_\odot}\right)^{-2/3} \qquad ms^{-1} \tag{1.2}$$

P and a can be derived using the 3rd Kepler’s law:

$$P = \left(\frac{M_*}{M_\odot}\right)^{-1/2} \left(\frac{a}{1AU}\right)^{3/2} \qquad yr \tag{1.3}$$

Regarding the formula 1.2 it is clear this method is useful for massive planets with short periods.

Concerning the threshold of the method let is notice K of the Sun−Jupiter system is 12.5 ms^{-1} (and 0.1 ms^{-1} for the Sun−Earth system). The present day threshold is approximately at 15 ms^{-1}. Further discussion of the radial velocity threshold is hereinafter.

Interferometry

Radial velocities could be measured using interferometry as well. Let us have several beams of light from one source. Then, because of different travel distances of different beams and due to the wave substance of light, the light beams interfere (constructively, or destructively).

[19] If the star-observer line lies within the orbital plane, then $i = 90°$; if the line of sight coincides with the axis of revolution, then $i = 0°$.

So the interferometers combine the light caught with different apertures; the higher distance of apertures, the higher resolution of the method. For the ground observations, the aperture distance is limited with size of the Earth. There have not been any exoplanets discovered convincingly using interferometry.

However, there are several interferometry projects being prepared with the highest expectations. For example, a very promising project is NASA Space Interferometry Mission. The satellite equipped with an optical interferometer would be placed at an Earth-trailing solar orbit; about 95 million km far from the Earth. The project should be able to discover terrestrial planets of approximately 250 nearest stars.[20]

Polarimetry

This method is based on another essential character of light – directions of oscillations of light waves are generally random (i.e. 'unpolarised light'). The stellar light is unpolarised as well. However, after collision with a planetary atmosphere, a beam of light could become a polarized one. This polarised part of light could be distinguished within the observed beam of light of the star-planet system and the planet discovered consequently.

Nevertheless, no planets have been found using this method yet. Further details see in [58] Schmid & al. (2006).

Astrometry

The gravitation influence of a planet causes (apart from the changes of radial velocity) a movement of a star around a center of gravity (a barycenter) of a star – planet system. The movement, distinguished from the proper motion of all the system through the galaxy, could be measured. Angular change of the star possition θ (measured in arcsec, hereafter as) can be estimated as

$$\theta \sim \frac{10^{-3} pc}{d} \left(\frac{P}{1yr}\right)^{2/3} \left(\frac{M_*}{M_\odot}\right)^{-2/3} \frac{M_P}{M_J} \qquad as \tag{1.4}$$

where the system distance from the Earth is d; the orbital period is P; the mass of the star is M_* and the mass of the planet is M_P.

A possibility to determine a planet's mass (without $\sin i$ parameter) should be underlined among the method's advantages. Yet, in comparison with radial velocity, the method could be successfully used for planets of long periods, large orbits and hot and fast rotating stars as well. On the other hand,

[20] See [69] Webpages of NASA SIM project.

the methods demands very high level of precision. The motion of a star – Jovian planet system, which is several pc far, requires measurements of order of hundreds μas. Regarding disturbances caused by the Earth's atmosphere, notice such a precision will be hopefully reached by space satellites.

Photometry of transits

If the Earth is approximately at the orbital plane of an exoplanet, the observer can see a transit of the exoplanet in front of its star (let us say 'an eclipse of a star') every orbital period. The decrease of light flux may be measured with photometry.

The light decrease amount is typically about 1% assuming a Sun-like star and a Jovian planet.

The analysis of the light curve can provide us with a diameter of the exoplanet. If also the radial velocity curve is available, the planet density can be estimated. Further, when the stellar light passes through the atmosphere of an exoplanet during a transit, the chemical composition of its atmosphere may be found via spectral analysis.

However, there are some disadvantages of the method. Firstly to be considered is the geometry of the system – the exoplanet, the star and the Earth must be perfectly aligned. Therefore it is necessary to monitor many candidate stars. However, such a task is manageable using automatic techniques. Secondly, there are many sources of signal noise[21], so false detections are likely to happen.

On the other hand, these measurements might be performed using even middle-size telescopes, so many groups of astronomers (of semi-professional level) are involved. A good example could be the project MARK of the public Stefanik observatory in Prague. More details can be found at [72] Webpages of Štefánik observatory.

Photometry of orbital phases

Concerning a giant planet orbiting a star, the planet undergoes different phases (e.g. like the planet Venus seen from the Earth), the total brightness of the system varies with the exoplanet's orbital period. Definitely, such a measurement would require very high level of photometrical resolution, which is not reachable nowadays. But hopefully the new generation of space telescopes can reach the needed resolution – see [31] Jenkins & al. (2003).

[21] I.e. stellar signal noise (e.g. stellar spots, features in stellar atmosphere) and terrestrial signal noise – seeing.

Eclipsing binary

Having a geometry similar to the previous cause of transit photometry – one star of the binary, the second one and the Earth perfectly aligned – the regular dims of the stellar light can be observed, as the stars eclipse each other.

If there is a planet on a circum-binary orbit[22], we may witness disturbances in predicted time of an eclipse, as the binary moves around the barycenter of the system the binary – the planet. Based on these disturbances, the presence of a planet can be detected.[23]

Following [49] Raghavan & al. (2006) it seems that planetary systems of binaries are not exceptional. Out of the sample of 131 exoplanets Raghavan & al. indicated a lower limit of 30 (23%) planetary systems having stellar companions. Moreover, at least three planet systems of the sample reside in triple-star systems.

Pulsar timing

The similar effect ('light time effect') provides us with the possibility to discover pulsars' exoplanets. After an explosion of a massive star[24] (supernova), a neutron star is formed as a very dense remnant. Pulsars, fast rotating neutron stars, emit radio beams in a direction of an axis of magnetic field. Having the magnetic field axis deflected from the ration axis, very regular radio pulses may be observed.

Due to the motion (revolution) of a pulsar around the barycenter of a pulsar-planet system, the difference $|\Delta t|$ between the predicted and really observed of radio pulse can be detected.

If the orbital period is P; the mass of the star is M_* and the mass of the planet is M_P, then

$$|\Delta t| \sim 1.5 \left(\frac{P}{1yr}\right)^{2/3} \left(\frac{M_*}{M_\odot}\right)^{-2/3} \frac{M_P \sin i}{M_\oplus} \qquad ms \tag{1.5}$$

Regarding pulsars of even milliseconds periods, even very small bodies within a pulsar system may be discovered – terrestrial exoplanets, dwarf exoplanets, or even small bodies.[25]

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[22]And there are clues the presence of planetary system embedded in curcum-binary disks can be rather common; according to [47] Pierens & Nelson (2007).

[23]See [12] Doyle & Deeg (2002); [11] Deeg & al. (2000) and [13] Doyle & al. (1998).

[24]E.g. 10 $M_\odot$.

[25]Following A. Wolszczan's report addressed on 25 October 2002 in Bonn (see [75]), there was a residual detected in the signal of pulsar PSR 1257+12, which can not be explained by the presence of a fourth planet. A. Wolszcan suggested: *"Since there is no gravitational effect evident in the 1400 MHz data, any compact body must have less than*

Yet, there is a question of the formation of such pulsar planets. There are several scenarios proposed: the planets could be formed with the former star (and 'survive' the supernova explosion); or they could be attracted from outer space (e.g. from the system of the second star in the binary); or they can be formed from an accretion disk after the supernova explosion as described before.

Gravitational microlensing

The concept of gravitational microlensing is generally attributed to A. Einstein (see [15] Einstein 1936). However, other astronomers were engaged in this question. Let us mention at least František Link, (1908-1984), the first head of the Astronomical Institute of Czechoslovak Academy of Science. F. Link formulated the formula of the increase of light intensity and published the results in French scientific journals[26] before [15] Einstein (1936).

Following the concept, heavy and compact space bodies can act as microlenses – through the deflection of light. The method works when a distant object, a microlens (e.g. a star) and the Earth are aligned. In light of a need for an almost perfect alignment of the objects, the microlensing effects generally occur only for, say, a few days and can not be repeated with the same objects.[27] However, there have been observed many microlensing events so far.

Concerning an exoplanet detection, if a microlensing star has a planetary system, there are measurable effects – the increase of light flux. Having such a light curve a mass rate of the planet and the star can be found (even regarding relatively small – terrestrial – planets), as well as a semi-major axis. However, this methods demands a continuous observation of a huge number of stars, as a single microlensing event is a very rare event.

There have been 4 exoplanets proved with microlensing so far – within a framework of Optical Gravitational Lensing Experiment ('OGLE') program using 1.3 m Warsaw telescope in Las Campanas, Chile (see [16] The Extraso-

1/5 the mass of Pluto, but such an object could still measure 1000 km – and survive for hundreds of millions of years in a pulsar's radiation field. Its surface would be ablated constantly, though, turning it into something like a comet: This 'coma' moving thru the line of sight once per orbit could be the cause of the periodic delays in the pulse arrival times. There is no way that this speculative scenario can be proven right away, but a year's more of timing data should confirm or deny the strict periodicity of the 430 MHz residuals – and these measurements are being made with Arecibo right now."

[26] See [37] Link (1936) and [38] Link (1937). Further details of the historical background of the gravitational microlensing concept can be found in [61] Šolc (1999)

[27] *"Of course, there is no hope of observing this phenomenon directly."* – Albert Einstein (1936).

lar Planets Encyclopedia; [70] Webpages of OGLE program and [20] Goud & al. 2006). Some other projects are ongoing – e.g. MOA at Mt. John Observatory in New Zealand (see [68] Webpages of MOA program) and PLANET, networking five approximately 1 m telescopes in the southern hemisphere ([71] Webpages of PLANET program).

Circumstellar disks

There are two main approaches of using a circumstellar disk to the detection of an expolanet.

1. For many deacedes, Be stars (B stars with gaseous circumstellar envelopes) have been studied. Observing the structure of a disk (via regular changes of H emission), it is possible to determine the presence of another star in the system. Beyond, the structure of a disk could be formed by massive planets as well. Especially a central cavity of the circumstellar disk may indicate the presence of planets – for example, the question of ϵ Eridani system, as discussed in [18] Greaves & al. (2005).

2. The analysis of a dusty circumstellar disk is probably more promising. It is generally believed that the radiative force expelles the dust away from the stellar systems. Therefore, if the dust disk still exist around old (evolved) stars, it must be obviously continuously supplement from the small bodies (comets, asteroids). Nevertheless, the origin of particular types of dust particles is still a question of discussion – see [8] Chen & al. (2007).

Direct imaging

All the other methods can be classified as indirect ones, they do not provide us with any image of an exoplanet itself, but follow signs of a planet's presence. As the exoplanets are very faint objects, relative to their parent stars), it is almost impossible to observe them directly (in the optical or IR wavelengths). Concerning the Sun-Jupiter system, the planet-to-star luminosity ratio would be approx. 10^{-9}.

However, four planets have been discovered via direct imaging so far – mainly the very massive (and bright) Jovian planets distant enough from the respective stars (i.e. at separations as large as some 100 AU). See [16] The Extrasolar Planets Encyclopedia.

A more promising prospect of the method was postulated out by [2] Biller & al. (2006). As there were many dwarf stars discovered recently within

5 pc from the Sun, low-mass companions (and even exoplanets) could be directly observed for then, because these systems are extremely nearby and intrinsically low luminosity, so the brightness ratio planet/star is much less extreme.

Furthermore, there are space projects of direct imaging: for example Darwin – the project of European Space Agency. Four or five satellites, equipped with mid-infrared 3 – 4 m telescopes, would be place at Lagrangian Point L2 (at the distance 1.5 million km from the Earth). Further information can be found at [66] Webpages of Darwin project.

Contact with some forms of extra-terrestrial life

Last and least probable source of information about extra-solar systems is a contact with some forms extra-terrestrial life. Many scenarios have been described in details in science-fiction literature in the past century.

Nevertheless, let us notice that the SETI program is still going on, in spite of null detection of any artificial radio signal so far. Currently, SETI Institute and University of California, Berkeley, are building Allen Telescope Array – 1 hectare radio telescope in California.[28]

1.2.3 Exoplanet classes

As mentioned above, the exoplanetary terminology is quite unclear. The following terms are often used:

Terrestrial (rocky) and Jovian (gas) planets – both of these classes are relatively well defined within our Solar System with a number of features: mass, density, chemical composition, supposed processes of formation, structure of moons and rings etc. However, it is likely intermediate planetary types will be found in other systems (see chthonial planets and super-Earths hereinafter). Further, there is a question whether huge planets of nearly brown dwarf masses could be called Jovian at all. For the purposes of this thesis, terms terrestrial and Jovian are understood in the broadest way – all the planets are generally either terrestrial, or Jovian.

Chthonial planets – this term was proposed by [26] Hébrard & al. (2003) for originally Jovian planets, which have lost their hydrogen atmosphere through the interactions with respective stars. The remaining core (rocky or metallic one) may resemble the terrestrial planets.

[28] According to [56] SETI webpages.

Super-Earths – the term has been broadly used for last two years for newly discovered terrestrial planets. According to [65] Valencia & al. (2007) super-Earths are a sub-class of terrestrial planets, differing from the planets of our Solar System. As the upper limit of the super-Earth mass is about 10 $M_{\oplus}$, the super-Earths can be considered as a terrestrial sub-class bordering on Jovian planets.

Hot Jupiters – generally, the term 'hot' is used for planets of smaller semi-major axis (e.g. 'hot super-Earth') – see e.g. [63] Teroquem & Papaloizou (2007). Hot Jupiters[29] are Jovian planets sub-class of mass close to or exceeding Jupiter's mass, but with semi-major axis of about 0.1 AU at the most. Therefore, they are more likely to be discovered using radial velocity or photometry of transits. Because of libration, their eccentricities are very low and the planets are believed to be tidally locked to the star.

Hot Saturns, hot Neptunes – there are several Neptune-mass planets discovered so far, so the term (hot) Neptune is generally used to distinguish (hot) Jovian planets of smaller mass than Jupiter. Neptunes therefore can be seen as a Jovian sub-class, bordering with terrestrial planets. Term Saturn can be understood likewise. However, it could be used for underlining the presence of a significant system of planet's rings – see [14] Dyudina & al. (2005). For the purposes of this thesis, the term (hot) Neptune is understood as described and the term (hot) Saturn is skipped.

Eccentric planets – the term was introduced by [42] Marcy & Butler (1996) to distinguish a planet 70 Vir B from hot Jupiters and Jovians of our Solar System. *"We propose referring to objects of 5-15 M_J with $e > 0.2$ as eccentric planets to distinguish them from the less massive giant planets, such as Jupiter and Saturn, which reside in nearly circular orbits. Such an empirical class would become useful only if orbital characteristics correlated with planetary mass or stellar characteristics, thereby suggesting a distinction in formation relative to the conventional 'giant planets' and 'brown dwarfs'."*

Of course, such a list of planetary classes and sub-classes can be neither exhaustive, nor consensual, nor definitive. For example, good reasons might

[29] Also called pegasids or pegaseans (51 Peg B), planets roasters, epistellar Jovians.

be found to split a category of hot Jupiters into two.[30] Yet, an occasional re-adjustment of terms is needed to avoid misunderstandings.

1.2.4 Statistics

In the light of a large and increasing number of exoplanets discovered so far, it is possible to explore the set of planets using various statistic methods. The fraction of stars having planets reaches 7%, based on the up-to-date knowledge – following [77] Wu & al.(2007), [54] Santos & all. (2004) and exoplanet catalogue [7] Butler & al. (2006).

Tab.1 – Detected exoplanets

Method	Planetary systems	Planets	Examples
Radial velocity	178	213	51 Peg B; 70 Vir B
Photom. of transits	23	23	GJ 436 B
Microlensing	4	4	OGLE-05-071L B
Direct imaging	4	4	AB Pic B
Pulsar planets	2	4	PSR 1257+12 B
Free-floating		3	S Ori 70
Total	211	251	

Table 1 shows the efficiency of different methods of detection following [16] The Extrasolar Planets Encyklopedia. Figure in Appendix I shows a fragmentation of discovered planets according to planetary mass and semi-major axis; further it shows expected capacities of several projects being in preparation.

Definitely, a more complex analysis can be done. [41] Marchi (2007) chose these parameters (as provided by [16] The Extrasolar Planets Encyclopedia): planetary mass, orbital period, semi-major axis, eccentricity, inclination, stellar mass and stellar metallicity Fe/H. Through a cluster analysis of the variables, he found 5 clusters. The clusters do not correspond to the planetary classes and sub-classes, as described above. However, the analysis shows a split of hot Jupiters into two groups regarding metallicity and mass of parent stars (compare with [21] Hansen & Barman 2007). Some general correlations between orbital parameters and metallicity were found (higher metallicities correspond to lower eccentricities).

To summarize the chapter, two comments on strong selection effect in the available sample of exoplanets should be made.

[30] Hansen & Barman identified two groups of hot Jupiters based on complex characteristics and proposed an intensity of Helium evaporation as a surprisingly important process in forming one of these two groups. See [21] Hansen & Barman (2007).

Firstly, due to the character of the detection techniques (namely radial velocity and transit photometry), mainly massive planets (e.g. hot Jupiters) with minimal semi-major axis have been found. Nevertheless, such planets could be rather exceptional ones.

Secondly, one can note a strong focus on terrestrial Earth-size planets more distant from the stars – within the 'habitable zone'. As mentioned in the introduction, this focus of the public, the media and the scientists is very natural as it is connected with essential questions of the origin of life. Therefore, most of long-term exoplanet programs (ESA Darwin, NASA SIM etc.) are designed to be focused on the Earth-like planets detection.

1.3 70 Vir (HD 117176) – current knowledge

70 Vir B is one of the first discovered exoplanets orbiting a Sun-like star. The basic properties of 70 Vir can be found in Table 2 and the comparison with our Sun in Table 3. [31]

The exoplanet 70 Vir B was discovered by G. W. Marcy and R. P. Butler in 1996.[32] The detection was preliminary confirmed by D. Naef & al. in 2001. Further, D. Naef & al. confirmed the orbital solution of Marcy & Butler more precisely.[33]

The corresponding orbital solutions are summarized in Table 4. Notice the large eccentricity of 70 Vir B – 0.4, compared to e.g. the eccentricity of Jupiter – 0.05. See [46] Perryman & al. (1996) for calculation of the mass limit of 70 Vir B.

Also note that both Marcy & Butler and Naef & al. based the calculations upon the mass of 70 Vir A of 0.92 $M_\odot$. That is in accordance with for example [53] Santos & al. (2004) (0.93 $M_\odot$), but the new measurements indicate 70 Vir A is heavier (see [17] Fischer & Valenti 2005). The data of Table 2 follow these new measurements.

[31] According to [0] The Extrasolar Planets Encyclopedia and [56] Fischer & Valenti (2005)

[32] Based on the spectra obtained at Lick observatory, using the high-resolution Hamilton echelle spectrometer, fed with the 3 m Shane and the 0.6 m coud auxiliary telescopes. See [42] Marcy & Butler (1996).

[33] Based on the spectra obtained with ELODIE echelle spectrograph mounted on 1.93 m telescope at the Observatoire de Haut-Provence. See [44] Naef & al. (2004).

Tab.2 – 70 Vir – basic parameters

Declination coord.[34]	+13 46 44
Right Asc. coord.	13 28 26
Mass ($M_{\odot}$)	1.1
Radius ($R_{\odot}$)	1.86
Apparent magnitude V	5
Distance (pc)	22
Parallax (arcsec)	0.112

Tab.3 – 70 Vir compared to the Sun

Parameter	70 Vir	Sun
Spectral type	G4 V	G2 V
$T_{eff}(K)$	5432	5780
Age (Gyr)	7.1	4.5
Metallicity [Fe/H]	−0.11	0.00
$P_{rot}(days)$	35	25.4
V $\sin i$ ($\mathrm{km\,s^{-1}}$)	< 3	1.8

Tab.4 – 70 Vir B – basic parameters

	Marcy & Butler		Naef & al.	
Parameter	Best-fit value	Uncertainty	Best-fit value	Uncertainty
Period (days)	116.67	0.01	116.689	0.011
e	0.40	0.01	0.397	0.005
ω ($\circ$)	2.1	2	359.40	0.92
$K_1(ms^{-1})$	318	4	314.1	2.0
$a_1 \sin i$ (AU)	0.00312	0.00004	0.00309	0.00002
$M_P \sin i$ (M_J)	6.6	0.1	6.56	0.04

Chapter 2

Measurements of orbital parameters

2.1 Technical framework

All the 70 Vir spectra were taken with the DAO[1] 1.2m telescope at the Coude focus with the 32121H spectrograph. Until May 2005, the detector used was the UBC-1 4096x200 CCD. Since May 2005, the DAO SITe-4 4096x2048 CCD was used.

There were on-chip binning (perpendicular to the dispersion axis) of 10 for the UBC-1 and 8 for the SITe-4. Each CCD pixel is 15 microns in size. After the binning, one got about 5 or 6 binned CCD rows. The recipocal dispersion was 10 Å/mm which gives a value of about 0.14 Å/pixel. The image slicer IS32R was used (a projected slit width of 60 microns), so getting a resolution of 4 pixels.

The 32121H spectrograph means it is a 1200 line/mm grating used in first order for the 32-inch camera. The H stands for a blaze wavelength of 6000Å. A field flattener was used since August 2005, resulting in higher resolution. S readout of 4200 points was done giving the extra from 4096 as floating-bias correction points. Tens of bias, lamp flats, and arc frames were taken. The average of those was used to preprocess the spectra. Finally, iraf's apall was used to extract the spectra from the 5-6 rows to 1-dimensional.[2]

[1]Dominion Astrophysical Observatory, Victoria, British Columbia, Canada. See [10] DAO webpages.

[2]Personal correspondence – courtesy Dr. Stephenson Yang.

2.2 Software framework - Essential used programs

Firstly, the essential used programs will be briefly described. Then, the used data analyzing procedures will be outlined.

2.2.1 SPEFO and BARKOR

The program SPEFO[3], broadly used at Astronomical Institute of Czech Academy of Science (Ondřejov observatory), was used for the first block of analysis. SPEFO have been used mainly for the reduction of data from the Ondřejov Reticon detector (1872 pixels, 12 bit A/D), however it can process data from other instruments too, provided that they are in FITS one-dimensional format. SPEFO provides the basic data reduction tasks such as the dispersion function multinominal fit, spectrum rectification, Fourier noise calculation, radial velocity and equivalent-width measurements.

As a great deal[4] of observed shift of spectral lines is caused by the motion of the Earth (by both the rotation around its axis and the revolution around the Sun), the correction is needed. To calculate the barycentric corrections of the radial velocities the program BARKOR, developed by Mgr. Marie Hrudková, was used.[5]

BARKOR provides with the barycentric correction of radial velocity and with the corresponding barycentric Julian date for the moment of the observation. There are two input files needed: the first one containing the object's coordinates, the respective epoch and the code of the observatory; and the second file containing the filenames of the spectra and dates of observations.

BARKOR was built upon several calculation methods. The process AABER1 by C. Ron and J. Vondrák was used to calculate the Earth velocity components towards the Solar System's barycenter. The process GEO by J. Vondrák was used to calculate geocentric Julian date. And finally, the procedures of the program BRVEL by S. Yang and J. Amor were used to calculate barycentric Julian date.

Following [29] Hrudková (2005), the radial velocity uncertainty may be estimated with approximately 2 ms^{-1}. However, under certain circumstances,

[3]Program SPEFO was written by the late Dr. Jiří Horn. The program has been further developed by P. Škoda and especially by Mgr. J. Krpata. Version 2, released on 6 September 2006, was used for the puposes of this thesis. More information can be found in [28] Horn & al. (1996) and [59] Škoda (1996).

[4]Several ms^{-1} or even a couple of tens of ms^{-1}.

[5]Following [30] Hrudková & Harmanec (2005). More detailed information about the program and the source code can be found in [29] Hrudková (2005).

the uncertainty could be significantly higher.

2.2.2 KOREL

The program was written by Dr. P. Hadrava of Ondřejov observatory. Following the user's guide ([23] Hadrava 2004) KOREL complements Ondřejov code FOTEL[6] (see hereinafter). FOTEL provides with orbital elements of a star system based on radial velocity curves. In order to obtain such a curve it is necessary to identify some spectral lines belonging to individual component stars, to measure their observed wavelengths and to calculate their Doppler shifts.

If the line widths of one or more components are larger than the amplitude of radial velocity (further 'rv') curve, the lines are blended and standard methods of measurement of the line centers are subjected to radical errors.

To overcome such problems the method of spectra disentangling was developed by Dr. P. Hadrava.[7] Having an input of observed spectra KOREL calculates orbital elements of a system and profiles of spectral lines of individual stars of a system. The disentangling method solves orbital parameters together with spectra separation and rv measurements (using a cross-correlation technique).

The cross-correlation is based upon an idea that the presence of the spectrum of a faint secondary component, blended with a stronger signal of hidden in a noise can be better revealed from overall coincidence with the observed signal than from some local features.

Having reduced and rectified electronic spectra (using e.g. SPEFO), the spectra can be transformed into a set of ordered couples of wavelength λ and relative intensity $I(\lambda)$.

The Doppler shift of spectrum is constant in logarithmic wavelength scale:

$$x = c \ln \lambda \tag{2.1}$$

The laboratory line wavelength is used as a referential one. In non-relativistic approximation

$$dx = c\frac{d\lambda}{\lambda} = rv \tag{2.2}$$

[6] And it complements the code SPEL (for solution of spectroscopic elements of binaries) as well.

[7] The method was independently developed by K. P. Simon and E. Sturm – see [57] Simon & Sturm (1994). However, the method by P. Hadrava implements Fourier disentangling, which is more effective.

Therefore, shift in x matches searched rv of the particular spectral line. The cross-correlation of the observed spectrum $I(x)$ with a chosen template spectrum $J(x)$ is

$$F(v) = \int I(x+v)J(x)dx \tag{2.3}$$

The cross-correlation indicates the velocity shifts at which a similar contribution appears in the spectrum.

It is important to obtain the source spectra of different orbital phases of the system. Further, an ideal template $J(x)$ should contain the same ratios of their strengths as the spectrum of component to be measured.

The principle of Fourier disentangling is described in [23] Hadrava (2004) as follows. Let us suppose that a multiple stellar system consists of n stars and that the spectrum $I_j(x)$ (where j=1…x) of each component in the time apart of being Doppler shifted according to the instantaneous radial velocity rv$_j$ of the star j at the time t. The composite spectrum can be then expressed as a sum of convolutions with shifted Dirac delta-functions:

$$I(x,t) = \sum_{j=1}^{n} I_j(x) * \delta(x - rv_j(t)) \tag{2.4}$$

Comparing such spectra obtained at different times, the method finds what is the same for all of them (the spectra $I_j(x)$) and what is changing (instantaneous rv). Having Fourier transformation the equation transforms into:

$$\tilde{I}(y,t) = \sum_{j=1}^{n} \tilde{I}_j(y) exp(ij\ rv_j(t)) \tag{2.5}$$

where $\tilde{I}_j(y)$ represents the Fourier transformation of spectra $I_j(x)$ at the particular point y.

The principle of disentangling consists in minimalization of the sum of integrated squares of differences between the observed and model spectra, which is supposed to be due to observational noise in $I(x,t)$:

$$0 = \delta \sum_{l=1}^{N} \int |I(x,t_l) - \sum_{j=1}^{n} I_j(x) * \Delta_j(x,t_l,p)|^2 dx \tag{2.6}$$

where Δ_j are some general broadening functions, which may involve not only the Doppler shifts, but possibly also some line-profile broadenings at the time t.

Solving the orbital parameters of a system, the non-linear terms appear in the formula, so the simplex method is used then.

2.2.3 FOTEL

Analogous to KOREL the program FOTEL was developed by Dr. P. Hadrava of Ondrejov observatory. Following the user's guide [22] Hadrava (2004) the program is used to solve both radial velocity curves and photometric curves of binaries. FOTEL enables the separate or simultaneous solution of light and rv curves of binary stars.

In the light of the diploma thesis task, we will focus on rv curves solution only. The used FOTEL, version 4 can include into a solution rv of the third component. However, within this thesis FOTEL was used for solving a two-component system only.

The primary and secondary object are supposed to move in Keplerian orbits around the barycenter:

$$r_{1,2} = \frac{a_{1,2}(1-e^2)}{1+e\cos\nu}, \tag{2.7}$$

$$\nu = 2\arctan\left(\sqrt{\frac{1+e}{1-e}}\tan\frac{E}{2}\right), \tag{2.8}$$

$$M = E - e\sin E \tag{2.9}$$

Following these formulas orbital parameters can be calculated.

The program input is a set of ordered couples of time and radial velocity (or photometric light intensity). The program output is presented as a set of numerous parameters (including orbital parameters), ordered groups of phase and radial velocity and O-C (i.e. observed-computed differences).

In comparison with KOREL, FOTEL provides with solutions of more parameters and with respective errors. Further, input data of different sources can be solved separately (as 'datasets') and later on merged if requested.

Both individual data and datasets can be introduced with relative weight. However, as FOTEL solves rv (or light) table there is no graphical output, as provided with KOREL, which works with continuous cut of a spectrum.

Further information can be found at [24] Dr. Hadrava's webpages.

2.3 Data analyzing procedures

The provided 70 Vir and comparative spectra were of fit data format. Therefore the data were converted into SPEFO format using the program FITS2RET. Then, the spectra were calibrated with the wavelength scale with SPEFO using the comparative spectra. The spectra were rectified: the spectral continuum was inset with a multi-nominal. The false pixels, caused by cosmic radiation, were removed to reduce the signal noise.

The programs HEC2[8] and BARKOR were used to calculate radial velocity corrections and Julian dates of the observations. HEC2 provides the heliocentric corrections and Julian dates; BARKOR provides the barycentric ones. The BARKOR results were evaluated as more matching and therefore the BARKOR results were used for further calculations.

The task of the thesis was to test the detection threshold depending upon different data analyzing procedures. So, after the rectification of the spectra, there can be distinguished the three steps of data analysis.

2.3.1 Step 1 – SPEFO rv measurements of the original spectra

The first possible process is to determine radial velocities ('rv') by measuring shift of absorption lines. 30 spectral lines ('metallic lines'; 'metallic rv') were used.[9] Too blended lines (see hereinafter) were skipped on the case to case basis.

The two important factors must be underlined.

Firstly, the measured radial velocities contain in addition to real motion of the system 70 Vir the correction caused by the motion of the Earth and the 'detector floating'. The Earth-motion correction can be calculated (using e.g. BARKOR or HEC2), but the 'detector floating', the movement of the electronic detector towards the zero point, is generally unpredictable. Furthermore, there is usually a different optical trajectory of the light of the comparison spectrum, so differences may appear.

The solution is to measure radial velocities of telluric (atmospheric) absorption lines, which are made by the Earth's atmosphere. The telluric radial velocities indicate the detector floating. If the telluric radial velocity and the correction are deducted from measured metallic rv, the real rv of the distant system is determined.

Therefore, 19 telluric lines (of H_2O and O_2) were used – too blended lines were skipped on the case to case basis.

The second problem is the blending of the metallic spectral lines with the telluric lines. This blending causes a very high uncertainty in measurements of radial velocity. However, it's not possible to avoid blending using following

[8]Developed by prof. P. Harmanec. The version 6, released in August 2006, was used.

[9]E.g. H 6562.817; Ca 6471.668; Si 6347.0910; Fe 6335.3370; Ni 6643.6380.

this branch of data analysis. Too blended metallic lines were skipped on the case to case basis.

2.3.2 Step 2 – Korel – spectra disentangling

Using the programs SN2 and SNVAHY, the signal-to-noise ratio was calculated for every spetrum. The signal-to-noise ratios together with the barycentric corrections and barycentric Julian dates were then used as an input for the program PREKOR.

The program PREKOR, developed by Dr. P. Hadrava[10], facilitates the preparation of data for KOREL. PREKOR cuts the proper spectral regions from the set of input rectified spectra, interpolates them into the equidistant logarithmic wavelength scale and writes them in the format required by KOREL.[11]

Program KOREL could be used to calculate orbital solution then. As KOREL applies on a cut of the spectra only (prepared with PREKOR), several different areas of the spectra can be used to calculate the orbital solution. Further, KOREL provides with an image of disentangled spectra. However, there were no convincin results of KOREL solution for the used spectra.

More precise results may be reached using the spectra disentangling process. KOREL provides with the possibility of clearance of telluric lines from the stellar (metallic) spectrum.

Following [23] Hadrava (2004) Figure 2.1 shows the hierarchical structure of the stellar system, as used by KOREL. The numbers in circles are used for component stars; the numbers in parenthesis are used for their orbits.

Concerning the hierarchical structure of KOREL's model of the stellar system the telluric lines may be regarded as a distant object revolting with one tropical year period. This method was firstly tested out by [25] Harmanec & al. (1997) for the binary V436 Per.

Hrudková Harmanec proved that this method could be used for a single star (regarded as a binary of a minor amplitude of the rv curve) as well. The method was tested for ALPHA Boo (Arcturus) – see [30] Hrudková & Harmanec. (2005), or [29] Hrudková (2005), page 30 et sequentes.

The process settles the stellar spectrum as the component star number 1 with the fictive second component star. The Earth revolting the Sun is considered as a component star number 5. While using KOREL, there are no parameters allowed to converge, the program is used to disentangle the

[10] The source code and further information are at [24] Dr. Hadrava's webpages.

[11] According to [23] Hadrava (2004), page 31.

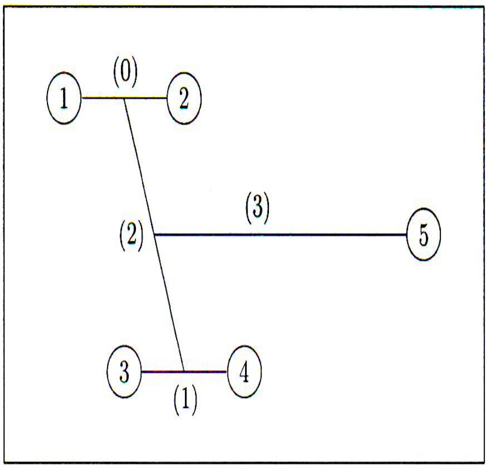

Figure 2.1: KOREL – the hierarchical structure of the stellar system

metallic and telluric spectra only.

The method is subjected to a following problem. The telluric spectrum does not include any continuum, but KOREL uses only one value of relative intensity of telluric lines in the spectrum. Relative intensity of the telluric line absorbing the stellar light of the continuum differs from relative intensity of the same line absorbing light in a center of a strong metallic line.

In [29] Hrudková (2005) the difference of intensity of the telluric line within a strong metallic line is estimated at even 50%. However, the method is still successfully applicable.

This method has been firstly used for purposed of extra-solar planets search as a part of this diploma thesis task. Having different cuts of the spectrum, the spectrum was disentangled into the metallic one and telluric one. The form of the spectra was a set of ordered couples of wavelength and relative intensity. This set was transformed into an ASCII file using the program KOS2, developed by P. Harmanec, in order to measure using SPEFO.

2.3.3 Step 3 – SPEFO rv measurements of the disentangled spectra

Both the metallic and telluric rv were measured using SPEFO then. It must be underlined that the measurements provides with only one value of radial velocity for metallic spectrum and one value for telluric spectrum. As SPEFO measures the shift of all the cut. That generally implicates a lower level of measuring errors caused by irregular shapes of lines. However, it is a question of discussion then, which of the lines of the cut should be regarded above others during the measurements.

Several cuts were analyzed using KOREL and SPEFO – e.g. 6180.0 Å (with the cut width 0.2 Å), 6190.3 (0.3) Å, 6208.6 (0.1) Å, 6270.0 (0.1) Å, 6277.5 (0.1) Å, 6333.2 (0.1) Å etc. Finally, two representative cuts were chosen for further analysis using FOTEL – 6266.0 (1.6) Å and 6275 (1.6) Å.

Chapter 3

Results and discussions

24 red spectra (6150-6750 Å), taken at DAO (see above) starting 12 April 1998 until 1 August 2006, were used for further analysis in all three following steps. Further, 4 red spectra (6170-6410 Å), taken at DAO starting 10 March until 23 June 2007, were used for the step 1 – SPEFO measurements. However, only a part of Fe lines, which were basically used to solve orbital parameters, was covered in these additional spectra.

Moreover, the table of radial velocities based on spectra obtained with ELODIE echelle spectrograph at the Observatoire de Haut-Provence, as published in [44] Naef & al. (2004), was used within steps 1 and 3 of the analysis.

3.1 The original spectra (step 1)

3.1.1 γ speed

As mentioned hereinabove both – the metallic and telluric lines – were measured using SPEFO. As using rather thin spectral lines, the Doppler shifts were measured with the focus on top of the lines, rather than on the line wings. Unblended lines were used only.

The final radial velocities (after deduction of barycentric correction and detector floating correction) include γ speed, the proper motion of all the system 70 Vir, as seen from the Earth.

The table of radial velocities was analyzed using the program FOTEL. Firstly, the radial velocities were divided into 6 datasets. The first dataset includes only H 3 line of 6562.817 Å. The second one includes three Ca I lines: 6439.083 Å, 6471.668 and 6717.687 Å. The third dataset was composed of Si I 38 (6721.844 Å), Si II 2 (6347.091 Å) and Sc II 19 (6604.600 Å) lines. The fourth dataset includes several Fe I lines and the fifth one Ni 43 (6643.638

Å) and Ni I 49 (6327.604 Å). The sixth dataset includes radial velocities as provided by [44] Naef & al. (2004).

Regarding the datasets 1-5 the signal-to-noise ratio (as provided with the programs SN2 and SNVAHY) was used as relative weight of single spectra.

Fistly, γ speed was calculated for each of these datasets separately to consider uncertainty of the datasets.

γ –e.g. the zero-levels of datasets – are calculated by direct least-square algorithm before the simplex method is used (see above subsection 2.2.2 KOREL).

Table 5 shows the results of γ speed calculations in comparisons with results of Naef & al. The comparison of the 6th dataset result with gamma speed provided by Naef & al. is very substantial. As the input table of radial velocities was the very same, the differences of the results show only differences of the used software. It is clear that both results are similar, but the uncertainty of FOTEL results is significantly higher.

Tab.5 – Step 1 – datasets' zero-levels

Source	Zero level ($km\,s^{-1}$)	Uncertainty ($km\,s^{-1}$)
Dataset 1: H	5.14	0.35
Dataset 2: Ca	4.62	0.49
Dataset 3: Si	4.65	0.73
Dataset 4: Fe	4.73	0.44
Dataset 5: Ni	4.61	0.62
Dataset 6: ELODIE	4.950	0.006
Naef & al. (2004)	4.951	0.001

It must be underlined that FOTEL[1] was designed for solving orbital solutions of binaries, i.e. for rv curves of significantly higher amplitudes (e.g. 1 km^{-1}). Nevertheless, we have presented that FOTEL can be used for solving orbital solutions of the star-planet system too, under specific limits of uncertainty.

Further, Table 5 indicates that (out of the datasets 1-5) the highest exactness can be reached on H, or Fe lines. Hence, for further calculations within the step 1 were used only rv of the dataset 4 (as a set of numerous Fe lines). The four spectra taken in 2007 were skipped, because only a few of Fe lines were covered by the spectra and high level of uncertainty distorted the results. Additional one measurement of highest uncertainty of original set was skipped.

[1]The very same can be said about SPEFO and KOREL.

3.1.2 Orbital parameters

FOTEL needs preliminary orbital parameters of a system as a part of an input file. The orbital solutions by Marcy & Butler (see Table 4, page 23) were used as such a preliminary input.

FOTEL allows choosing, which of the orbital parameters will be fixed on the input values and which ones will be converged (recalculated). Firstly, eccentricity was fixed on the value 0.4 and period, periastron epoch, periastron longitude and K_1 were converged. The results can be found in Table 6.

Tab.6 – Step 1 – orbital parameters – 1st calculation

Parameter	Best fit value	Uncertainty
Period (days)	116.32	0.27
Epoch (JD)	50033.2	7.9
ω ($\circ$)	245	33
$K_1(ms^{-1})$	450	170

Secondly, the periastron longitude was fixed to (following orbital solution of Marcy & Butler). The results can be found in Table 7. Finally, eccentricity, periastron longitude and K_1 were fixed; period and epoch converged. Table 8 shows the results.

Tab.7 – Step 1 – orbital parameters – 2nd calculation

Parameter	Best fit value	Uncertainty
Period (days)	116.62	0.57
Epoch (JD)	50052	12
ω ($\circ$)	358	fixed
$K_1(ms^{-1})$	250	150

Tab.8 – Step 1 – orbital parameters – 3rd calculation

Parameter	Best fit value	Uncertainty
Period (days)	116.49	0.51
Epoch (JD)	50055.0	9.5
ω ($\circ$)	358	fixed
$K_1(ms^{-1})$	315	fixed

It can be seen that only period and epoch (as provided by the second and third calculation) properly consist with solutions of Marcy & Butler and Naef & al.[2] and the uncertainty is lower. Studied values of rv are

[2] Compare to epoch 48900.39 +/- 0.33 as provided by [44] Naef & al. (2004). $Epoch = JD - 2400000$.

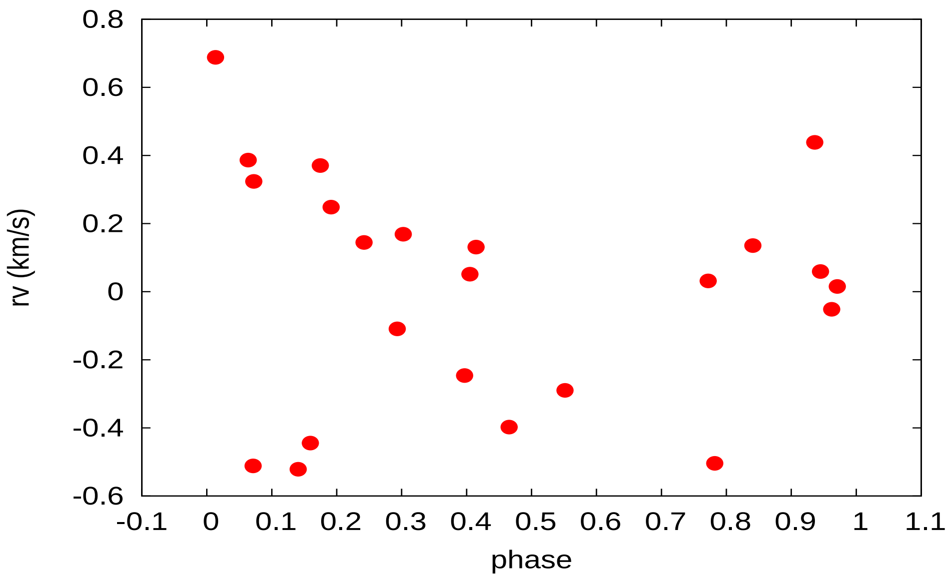

Figure 3.1: Step 1 – the curve of Fe radial velocities

quite small in comparison with noise brought by both observation techniques (spectroscopes) and by software analysis (see the comparison of FOTEL and Naef & al. results for the dataset 6 above).

Therefore, no further analysis (e.g. O-C, observed-computed, diagram) can be done within this step 1.

Nevertheless, particularly the results of period are reliable and matching. They demonstrate the 'classical' process of analysis rv curves of binaries (i.e. measurements using SPEFO and FOTEL analysis), as performed at Ondřejov observatory and Charles University, can be used for rv curves of exoplanets too.

The Figure 3.1 shows a curve of Fe radial velocities based on the second calculation of step 1. Although the data noise is significant (e.g. the points at phase = 0.1), the velocity curve is rather distinct.

3.2 The disentangled spectra (step 3)

The higher expectations were connected with step 3 of the analysis. This process (spectra disentangling using KOREL and further measurements of disentangled spectra using SPEFO) has been used for exoplanet rv curves firstly within this thesis.

For the FOTEL analysis, there are the three datasets distinguished. The dataset 9 includes rv measured on 6266.0 Å cut; the dataset 10 includes rv

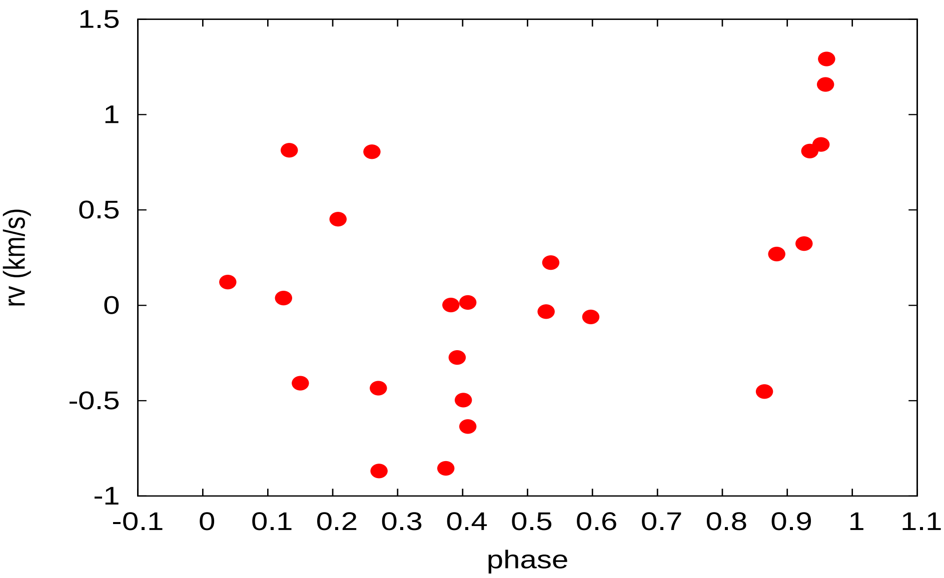

Figure 3.2: Step 3 – the curve of rv dataset 9

measured on 6275.0 Å cut and the dataset 11 is composed of rv provided by [44] Naef & al. (2004).

Firstly, the zero-levels – γ speeds – were calculated for each of the datasets separately. The results are shown in Table 9. The results indicates quite high level of uncertainty of datasets 9 and 10. Next, it can be seen quite a substantial value of γ speed of datasets.

Tab.9 – Step 3 – datasets' zero-levels

Source	Zero level ($\mathrm{km\,s^{-1}}$)	Uncertainty ($\mathrm{km\,s^{-1}}$)
Dataset 9	0.21	0.50
Dataset 10	0.14	0.48
Dataset 11 – ELODIES	-0.001	0.006

Because of this difference in γ speed the orbital solutions were calculated separately for the datasets 9 and 10. Period, epoch and K_1 were calculated, the other parameters were fixed as provided by Marcy & Butler. The results of the calculation are shown in Table 10.

Concerning previous analysis and results by Marcy & Butler and Naef & al., notice rather consistent results of period (and epoch). However, results of semiamplitude K_1 are significantly higher, even regarding the level of uncertainty. Figures 3.2 and 3.3 show the particular rv curves.

Tab.10 – Step 3 – separate datasets 9 and 10

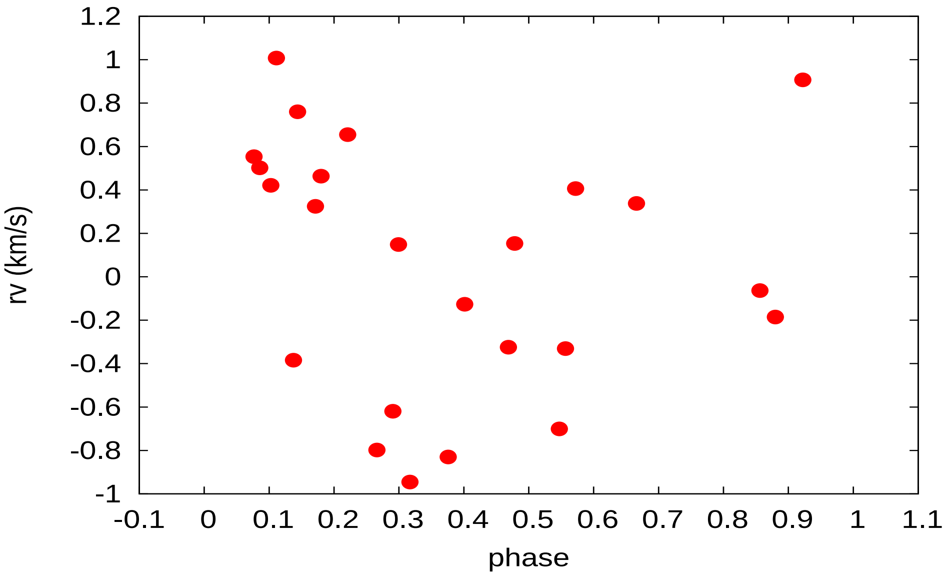

Figure 3.3: Step 3 – the curve of rv dataset 10

	Dataset 9		Dataset 10	
Parameter	Best fit value	Uncertainty	Best fit value	Uncertainty
Period (JD)	116.01	0.37	117.01	0.46
Epoch	50058.3	8.1	50033	11
$K_1(ms^{-1})$	600	110	730	110

As the results are rather poor, for the next calculation the datasets 9 and 10 were merged. The relative weights of the datasets were set to be 1 for both of them. In order to merge the sets, γ speeds (as indicated in Table 9) were deducted from the respective rv. Table 11 and Figure 3.4 show the results. The lever of uncertainty is lower, but still the results of K_1 are not satisfactory.

Tab.11 – Step 3 – merged datasets 9 and 10

Parameter	Best fit value	Uncertainty
Period (days)	116.07	0.25
Epoch (JD)	50056.5	5.6
$K_1(ms^{-1})$	590	73

Finally, all three datasets were merged; the datasets 9 and 10 after deduction of γ speed, as described above. Concerning the individual relative weights of the spectra all weight were set 1. However, the differences in accuracy of rv of dataset 9 (or 10) and 11 are significant. To calculate the

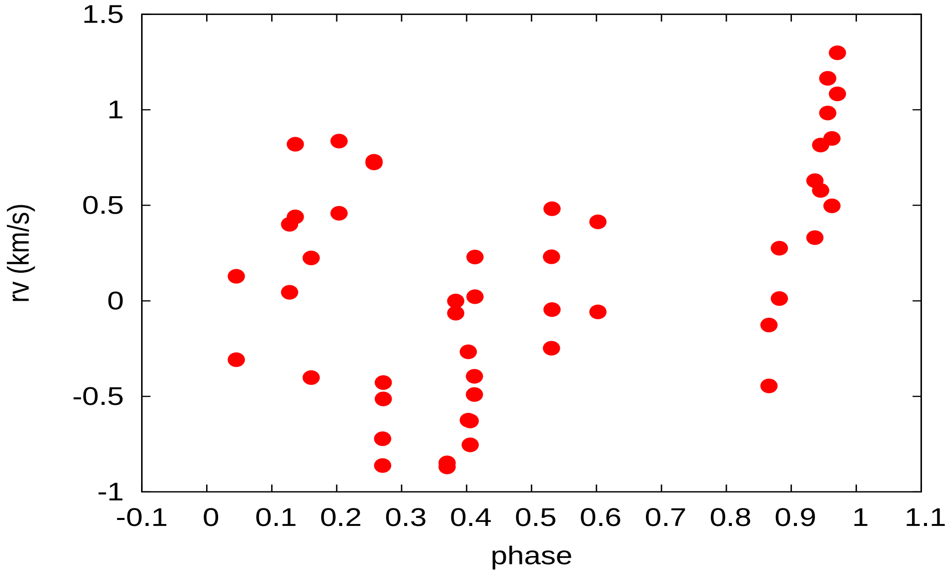

Figure 3.4: Step 3 – the curve of rv of merged datasets 9 and 10

adequate datasets' relative weight (W_j) the uncertainty rms_j provided by the first calculation (all the parameters fixed; Table 9) was used by the program SNVAHY as follows:

$$W_j = \frac{\frac{1}{rms_j^2}}{\frac{1}{rms_a^2}} \tag{3.1}$$

where rms_a^2 is a mean value of rms_j. The results of the calculation are shown in Table 12 and Figure 3.5.

Tab.12 – Step 3 – merged datasets 9, 10 and 11

	This thesis		[44] Naef & al. (2004)	
Parameter	Best fit value	Uncertainty	Best fit value	Uncertainty
Period (days)	116.688	0.010	116.689	0.011
Epoch (JD)	50040.24	0.15	48900.39	0.33
$K_1 (ms^{-1})$	317.1	1.8	314.1	2.0

Figure 3.5 clearly show the differences between the datasets 9 (10) and 11, as the rv curve determined by the dataset 11 can be clearly distinguished.

As the relative weight of the dataset 11 was approximately 7000 times higher than relative weights of the datasets 9 and 10, the solutions are were similar to Naef & al. However, having a longer time scale, some marginal improvements may be seen, as the level of uncertainty is slightly lower than in Naef & al.

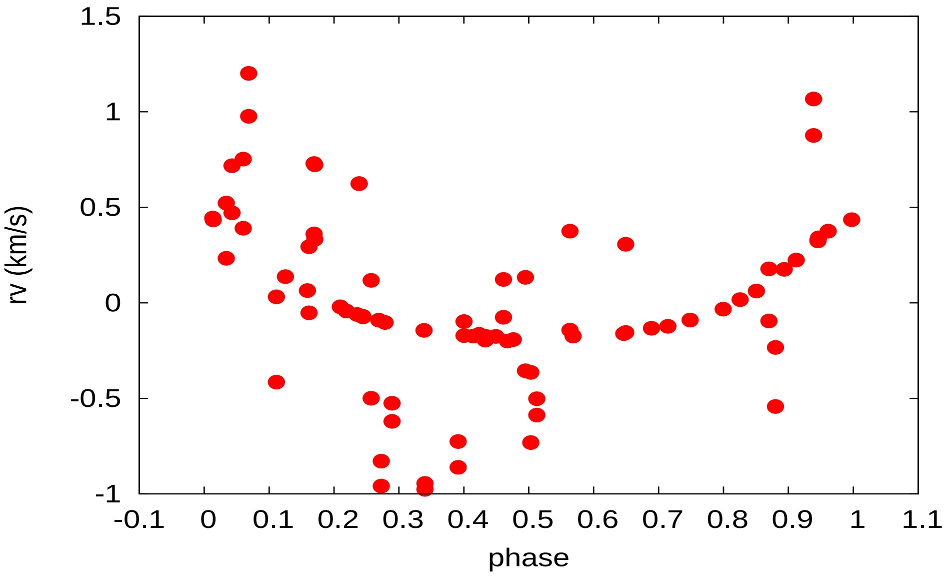

Figure 3.5: Step 3 – the curve of rv of merged datasets 9, 10 and 11

3.3 Perspectives

The consequent question after the prove of the existence of 70 Vir b is the existence of other planets within the system. Following the todays favored theories, Jovian planet 70 Vir b was formed in outer part of the system and then migrated closer to the parent star.

Following [40] Mandell & all. (2007) the models show that such migration do not exclude a possibility of formation of other planets. Moreover, the material shepherded in front of the migrating Jovian planet could accrete into (hot) Earths. Concerning 70 Vir habitable zone see [32] Jones & al. (2005).

There might be, say, three ways of increasing knowledge about the system distinguished. Firstly, development of spectroscopic observational techniques. See [5] Branne & al. (1996) and [9] Cumming & al. (1999) for technical information about the spectroscopes used for rv measurements.

Secondly, there are advancing other sources of information about the planetary systems (including orbital parameters). For example, radioastronomic attempts (see [36] Lazio & al. 2004) and studies of the stellar metallicity, which can correlate e.g. with exoplanet's semimajor axis (see [48] Pinotti & al. 2005).

And finally, lower level of uncertainty can be reach using more input data, as shown in step 3 of the analysis.

Conclusion

The contemporaneous knowledge of exoplanet research was resumed and briefly discussed. The terminology used in connection with exoplanet was discussed and working definitions suggested.

The core of this diploma thesis can be called 'the methodology study'. Using the set of spectra taken at DAO, Canada, two branches solution were tested and compared. Firstly, metallic lines of DAO spectra were measured using SPEFO and analyzed using FOTEL. Secondly, the spectra were disentangled using KOREL, measured using SPEFO and analyzed using FOTEL. The second branch included the merging of DAO spectra with spectra provided by Naef & al. The fundamental question was if this data analyzing framework (SPEFO, FOTEL and KOREL developed for analysis of binaries) and the disentangling technique can be used for exoplanet research (i.e. significantly lower amplitudes).

The answer is confirmative, but the need to base analysis on a significantly bigger set of spectra to get more accurate results appeared.

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Used abbreviations: A & A – Astronomy and Astrophysics; ApJ – Astrophysical Journal.

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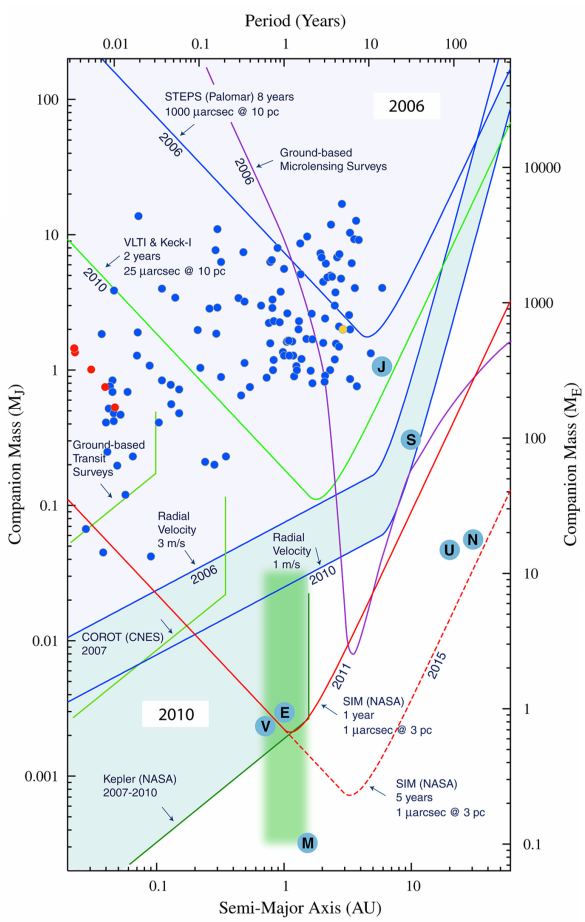
Appendix I



Courtesy NASA.