CHARLES UNIVERSITY
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FACULTY OF MATHEMATICS AND PHYSICS

Characterization of exoplanetary candidates from mission K2 – measurements of radial velocities

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Contents

Abstract

The first exoplanet discovered with the method of radial-velocity measurements was 51 Pegasi b in 1995. Since then over 2000 exoplanets were discovered and confirmed, with huge contribution of Kepler mission. The mission is based on method of transit photometry which allows to observe a huge number of stars at one moment. Kepler finds candidates for extrasolar planets. These candidates need to be confirmed with independent measurements of radial velocities. This is just the right task for meter-class telescopes which are the best option for their availability and number around the globe. In 2013 K2 mission started and now the telescope is observing chosen star fields in the north sky. Its targets are bright enough to be observed with the 2-meter telescope at Ondřejov observatory. OES spectrograph has a sufficient accuracy for identifying „false positive“ detections or decide whether the star could have an exoplanet.

This project intends to help student learn basics of the spectroscopy measurements. Student will work with Kepler/K2 archive and observe with Perek 2-meter telescope. Data from the OES spectrograph will be processed and analysed with IRAF software resulting in the phase diagram of radial velocities. Thanks this result we can characterize the target. In case of confirming the exoplanet, student will take part in proposing for time for follow-up observations using large telescopes (for example ESO telescopes). Three to five stars are expected to be observed and analysed.

1 Motivation

In last years, extrasolar planets became one of the main topics in astronomical research. Their study is crucial for looking for extraterrestrial life. It can also reveal the origin of life on the Earth. With more and more discoveries of extrasolar planetary systems we receive even more detailed information about the Solar system, its creation and development.

The Kepler space telescope (KST) discovered a huge number of exoplanet candidates (Borucki 2016 [1]). At this moment K2 mission is running an it is producing new candidates. The follow-up observations are needed for their confirmation and characterization. For these purposes observations at the ground-based observatories with the small and middle-size telescopes are the most efficient way. Thanks to their number and availability of observing time a large number of data can be acquired. Also, KST uses the method of transit photometry which is not able to determine all the parameters of potential exoplanet on its own. It needs to be combine with another method, mostly the spectroscopic method of radial-velocity measurements. This method is used by many small ground-based observatories which have sufficient resolution and accuracy what is needed for the measurements. With meter-class telescopes, such as 2-meter Perek tesecope at Astronomical Institute of Czech Academy of Sciences, we can observe even confirmed exoplanets to gain more statistical data, which are crucial for better understanding of the topic.

Generaly, the exoplanet candidates are discovered with photometry of transit. When the planetary orbit lies in the line of sight with the parent star it periodically passes in front of the star. This event is called transit and it causes a decrease in brightness of the star.

When knowing the period and other basic parameters, low resolution spectroscopy is used to determine the spectral type of the star. Just after that the method of high resolution spectroscopy is used to get radial velocities of the star.

Many exoplanet candidates are rejected in the process as they are categorized as false positives. Their photometric variations are not caused by transit of exoplanet. These stars are mostly binary stars.

The main goal of this project is to learn how to observe Kepler candidates, process obtained data and analyse the results. Three to five candidates are observed and their radial velocities are obtained. Accuracy of the OES spectrograph at the Perek telskope can be determined from the results.

2 The method

Doppler spectroscopy or the radial-velocity method (Bozza et al. 2016 [2]) is one of the most efficient and widely used method for research of extrasolar planets. It is indirect method based on observing the gravitational influence of the exoplanet on a parent star. As the planet is orbiting the star, it can produce small changes in position and velocity of star as they observe around common center of mass. This center of mass does not even need to be outside of the star. The velocity variations are detected thanks to the Doppler effect. The whole effect is stronger for heavy planets. The method can be used also for discovering and studying the brown dwarfs and eclipsing binaries.

Radial velocities are determined from the star spectra as the shift of the spectrum (spectral lines respectively). This shift can be measured in comparison with a radial velocity standard star or telluric lines in the star spectrum. Telluric lines are spectral lines caused by the Earth's atmosphere. Molecules in the atmosphere absorb and emit their own light which contaminates the star spectrum. However, telluric lines can be useful because their position in the spectrum is stable independently on the star spectrum so it can be used for determining the Doppler shift (Griffin et al. 1973 [3], Guenther et al. 2003 [4]).

For the radial-velocity measurements only the position (shift respectively) of the spectral lines is necessary. Intensity or shape of the spectral line is not important. However the shape of the spectral line can affect fitting of the crosscorelation function and change the value of radial velocity in some cases. Obviously a high signal to noise ratio is important for accurate measurements of radial velocities. High spectral range of OES spectrograph is advantage, but it is not necessary for determining radial velocities.

With method of radial-velocity measurements various parameters of the exoplanet can be determine. Planetary orbit radius can be calculated from the period of radial-velocity changes (star mass is needed) using Kepler's third law of planetary motion. From this calculation it is possible to determine the velocity of the planet around the star, according to Newton's law of gravitation and the orbit equation. Assuming the knowing of inclination of planet's orbit it is easy to calculate the real mass of the exoplanet (however this value may be just approximate as it depends on many parameters). Inclination is usually determined from photometry of transiting exoplanet. This shows why these two methods are so commonly used together (as the first photometric measurements are done and then the radial velocities are determined).

3 Instrument

For the target stars observations the Perek telescope at the Ondřejov observatory of Astronomical Institute of Czech Academy of Sciences is used. It is a coudé system on equatorial mount. The primary mirror is parabolical mirror with diameter 2 meters and focal ratio 1:4,5. Secondary mirror is convex hyperbolical with diameter 0,58 meters. Effective focal length of the system is 63,5 meters and effective focal ratio is 1:32.

At first the star light goes to the parabolic primary mirror which reflects it to the secondary mirror. From there the light is send through two flat mirrors and the splitting plate to the coudé focus. For the spectroscopy is used OES (Ondřejov Echelle Spectrograph). There is a slit located in the coudé focus from which the light goes to an f/32 collimator (focal length of 4637). From the collimator light travels to an echelle grating (blaze angle 69°, dimensions $420 \times 165 \times 74$mm with $54,5\text{g}\cdot\text{mm}^{-1}$. It is the most valuable optical component. It divides spectrum into Echelle orders. However these are still overlapped after crossing the grating. The light goes to white pupil what is the white image of grating (diameter 142 mm) but reduced to a diameter of 95 mm. After white pupil the light comes to the crossdisperser - a 54,5 ° LF5 prism placed in front of a CANON EF 200 f/1,8 camera lens (f=200). A scheme of the OES spectrograph is shown in the figure 1.

Result image is Echelle two-dimensional spectrum with approximately 56 orders covering spectral range from 380 nm to 950 nm approximately. Infra-red part of the spectrum is not used in data reduction because of the fringing effect (visible in fig. 4), so only the spectrum between wavelengths 4000 nm and 7400 nm is used. Spectrum is recorded on an EEV 2048 × 20148 array with 13,5 μm. It is a commercially available system including the dewar and controller. Starting 450 nm an uncovered gaps in the spectrum between neighbouring orders start to appear. This must be corrected in the reduction process. However all the important lines of hydrogen and helium are well covered.

Instrument parameters and technical information of OES are quoted from P. Koubský et al (2004) [5].

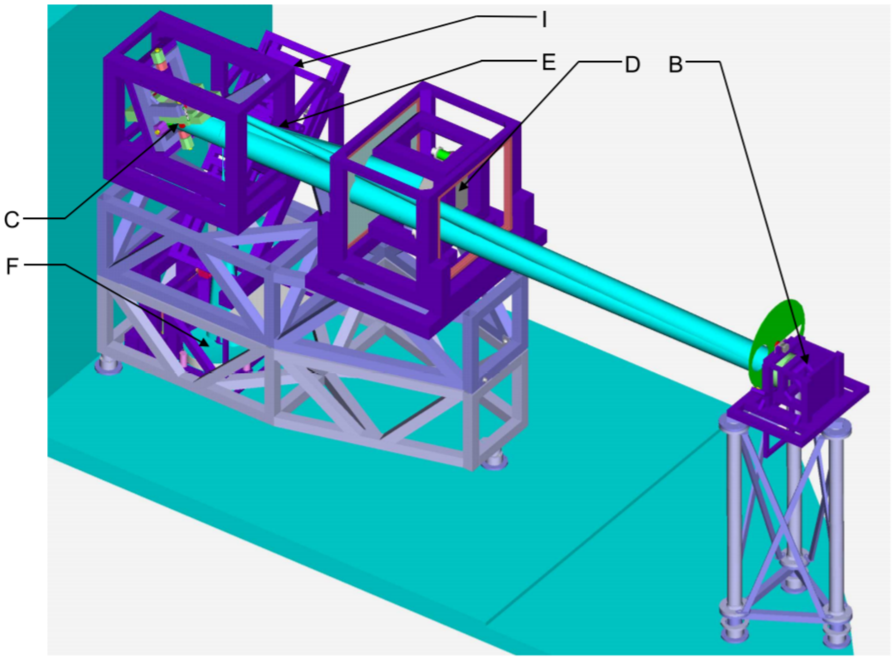

Figure 1. Scheme of the OES spectrograph: **B** collimator, **C** Echelle grating, **D** parabolic mirror, **E** small flat mirror, **F** secondary collimator, **I** CCD detector. P. Koubský et al (2004) [5].

4 Observational data sets and targets

I chose targets for my observation from Kepler mission K2 candidates at NASA Exoplanet Archive [6]. Chosen stars had to be brighter then 11 magnitude and observable from Ondřejov observatory of AI CAS at least for three months during the period between May and December 2017. Transit depth was limited for 1% – 5%. Chosen targets were categorized as candidates for exoplanets or candidates for eclipsing binaries at the time of selection (March 2017). List of chosen targets and their main parameters is shown on the table 1 (data used from NASA Exoplanet Archive [6] and SIMBAD Astronomical Database [7]).

Star	K2 campaign	V mag	P [days]	Spectral type	Nights	Images
HD 99458	1	8,16	2,72	A4 IV	10	30
HD 210803	3	9,50	2,57	K2 IV	5	16
HD 23765	4	9,43	1,69	F8 D	8	19

Table 1. Basic specification of chosen targets - observing campaign of Kepler K2 mission, brightness, orbital period P in days and spectral type. Table shows the number of nights when the object was observed and total number of taken images.

HD 99458 (Barros et al. 2016 [8]) was observed from March to November 2017. During 10 nights 30 images were taken. HD 210803 (Vanderburg et al. 2016 [9], Crossfield et al. 2016 [10]) and HD 23765 (Barros et al. 2016 [8]) were observed between July and October

2017. In sum 16 images during 5 nights were taken for HD 210803 and 19 images during 8 nights were taken for HD 23765. Primary conditions for the observation of targets were the weather conditions which limited observing time the most. I have tried to observe the targets in different orbiting phase for more continuous phase diagram. However this was limited by number of night with sufficient weather conditions.

Atmospheric conditions for spectroscopic observations are not so strict as for the transit photometry. The most important condition for the observation is the clear sky (or at least most of it). The humidity is also a determining parameter since it is not possible to observe when the humidity is 90% and more because of the high risk of condensation on the primary mirror.

It is necessary to take the whole set of images (bias, flat, dome flat, comparative). Before the first scientific image I took 10 bias frames and 10 flat lamp frames. Before and after any scientific image I took two comparative frames. Thorium-Argon (ThAr) lamp is used as the source for the comparative images. After the observation I took the dome-flat frames (this is necessary only one or two times a week). For the data reduction I usually take 10 or more dome flats.

Bias or zero frames (fig. 2) are images taken with zero exposition time and they are used for removing the readout signal from camera sensor. Flat frames are used for correction of optical imperfections created in optical path of the star light. For taking a flat image the sensor must be evenly illuminated by the light. There are two types of flats. For flat lamp images is the used lamp near the camera sensor and the light does not go through the whole optical path. On the contrary the source of the light for domeflats (fig. 4) - halogen lamps - is located in the telescope dome, so the light goes through the same path as the star light. Halogen lamps are not shining straight to the telescope but the light is reflected on canvas in front of the telescope so the light is homogeneous. Obviously, it is better to use dome flats for better data reduction and higher accuracy.

Since the spectrum of thorium-argon lamp is well described, ThAr lamp is used as the source of light for comparative images (arcs, fig. 3). They are used for the spectral line identification.

Scientific images are taken in series of two - four images in case some of them are not usable for analysis. This also gives more data for one time interval what increases the statistical accuracy. The image is taken when the star culminates or shortly before or after culmination. Exposure time is taken with respect to highest signal to noise ratio. For objects I observed it was mostly 900 or 1800 seconds. In figures 5 and 6 is comparison between two science images - image on the left is the raw image, on the right figure is completely reduced science image. Both are images of HD 210803.

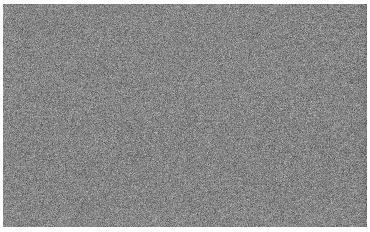

Figure 2. Bias image.

Figure 3. Arc image.

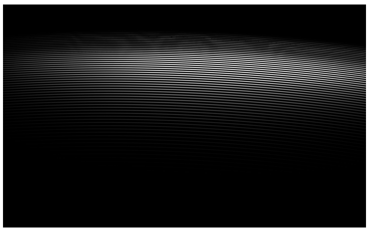

Figure 4. Domeflat image.

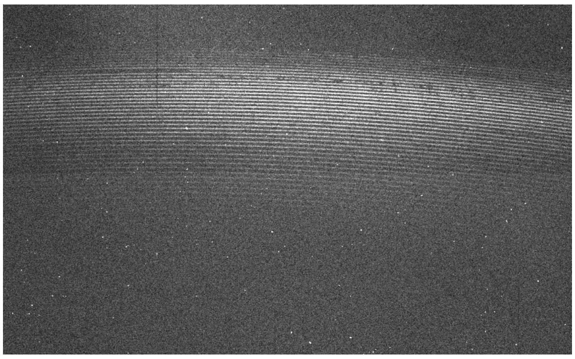

Figure 5. Raw science image with no correction - HD 210803.

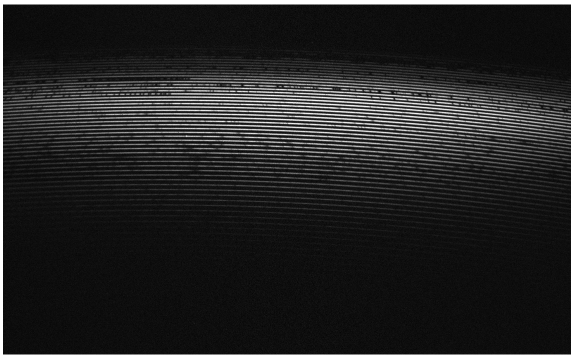

Figure 6. Reduced science image - HD 210803.

5 Data reduction

For the data processing I have used program IRAF (Image Reduction and Analysis Facility). The whole process can be divided into four parts. Before the beginning we usually correct the images of cosmic rays and bad pixels. At first I made some basic corrections such as the correction of bias and flat. I started with set of 10 bias frames and created the master bias image as the median image. Then the master bias correction was applied on all images. In one of the flat images (or image of some bright star, for example Vega) I identified echelle orders (or apertures) and I used it for reidentification of orders in other pictures. Then the master flat was created and all images were reduced of master flat. In the second part, after the reidentification of apertures for arcs and science images I identified spectral lines and found the wavelength solution for one of the arc images. This wavelength solution was then applied for other science images. In the third part I did the rectification of the spectra. Result of this process is one-dimension normalized spectrum. An example of the spectrum is shown in the figure 7. This spectrum is prepared for determination of radial velocity, what is fourth and the last part of the data analysis.

To determine the radial velocity from the star spectrum I used IRAF task fxcor, which fits the crosscorelation function and directly calculate relative radial velocity from the Doppler shift compared to used template. As the template I used the best image with the highest signal to noise ratio. Every value has to be correlated according to the relative radial velocity of telluric lines which in general are stable in time. Their small shifts need to be corrected in resulting radial velocities. A significant shifts of telluric lines would mean a problem with the data. At last I calculated orbital phase for each image from NASA Exoplanet Archive [6] data.

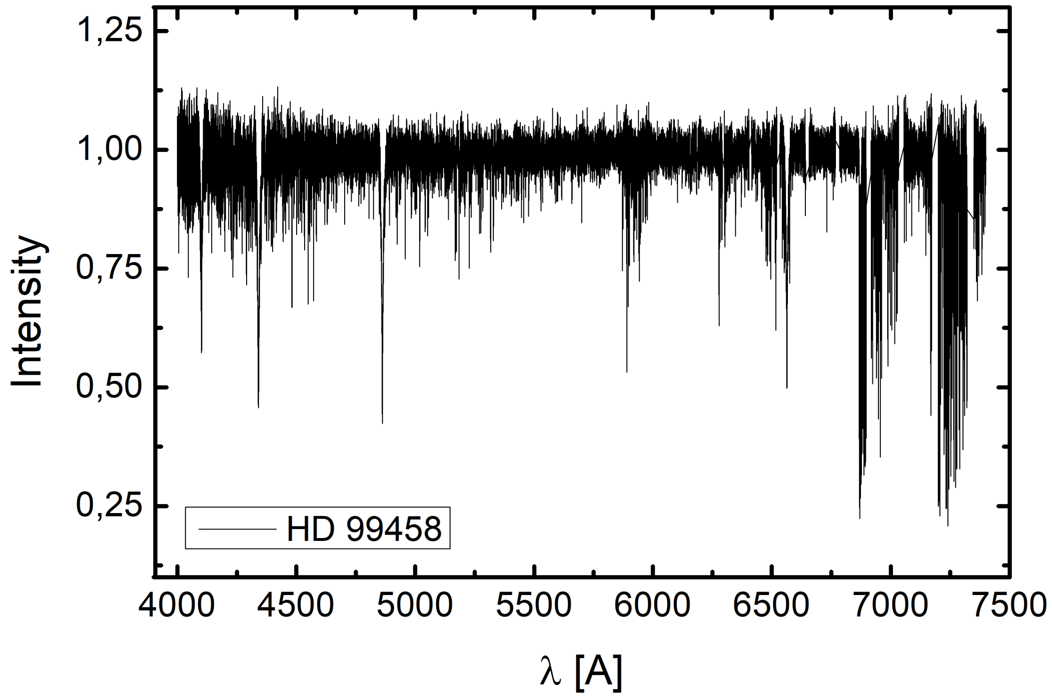

Figure 7. Result spectrum of HD 99458.

6 Results

6.1 HD 99458

HD 99458 was observed for the longest period of time and has a well covered phase curve. Ruselt radial velocities are written in table 2. Phase diagram is shown in figure 8. The result value of radial velocity for image is calculated as average of radial velocities determined for 8 intervals at wide-range spectrum from OES. For fitting the crosscorelation function I used spectrum from 400 nm to 600 nm divided into 8 intervals of 25 nm, standard deviation is calculated as statistical error from these values. The range was chosen in respect to position of telluric lines. Those are significant in red part of spectrum so the range is shift more to the blue part (where telluric lines interfere less). For telluric line correction I chose the most significant telluric lines between 686,7 nm and 689,4 nm.

As stated higher, HD 99458 has an orbital period $2,72$ days. The phase diagram shows the variations of radial velocities with amplitude around 60 km/s. These high variations show the star is spectroscopic binary and so the variations are not caused by an exoplanet. I plan to study the system further and characterize it in detail.

Phase	RV [km/s]	σ [km/s]	Phase	RV [km/s]	σ [km/s]
0,403	19,09	0,74	0,693	56,32	0,39
0,411	20,1	2,2	0,578	52,86	0,34
0,421	20,6	2,5	0,585	52,59	0,55
0,762	55,38	0,35	0,601	54,4	1,3
0,770	55,1	1,3	0,609	54,15	0,62
0,269	-5,49	0,61	0,265	-9,0	2,5
0,277	-3,77	0,40	0,273	-7,1	1,7
0,284	-3,37	0,28	0,939	19,65	0,84
0,292	-3,09	0,59	0,943	19,32	0,75
0,314	0	0	0,947	18,01	0,41
0,322	0,95	0,42	0,301	-4,56	3,9
0,330	1,51	0,47	0,305	-1,7	4,1
0,338	2,63	0,42	0,309	-5,3	5,1
0,677	57,29	0,33	0,059	2,8	1,6
0,685	57,73	0,28			

Table 2. Radial-velocity measurements for HD 99458.

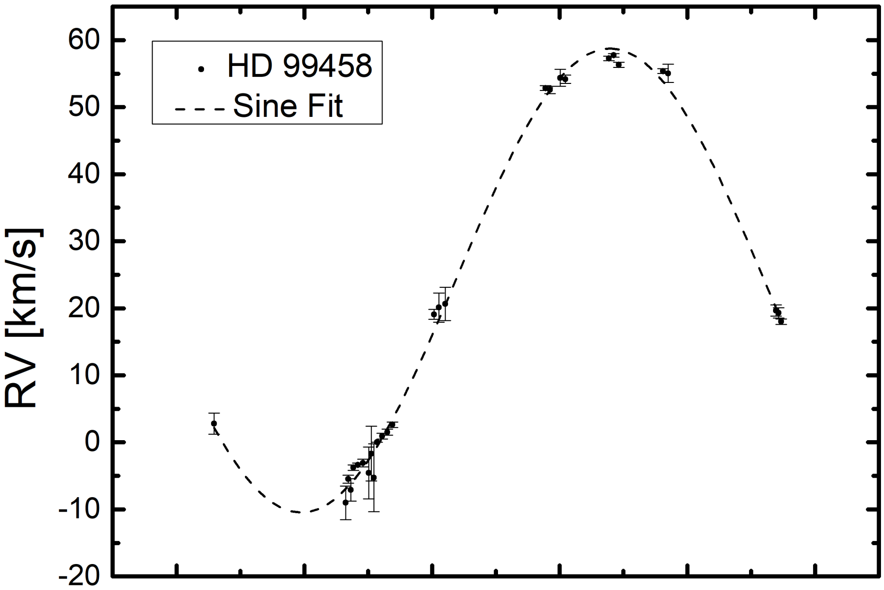

Figure 8. Phase diagram of HD 99458 radial-velocity measurements.

6.2 HD 210803

Results for HD 210803 are similar as the results for HD 99458. I have only 16 images from 5 nights and there are no data for phases $0,4$ - $0,9$. However it is possible to see the periodicity in the phase diagram 9 from obtained data. The radial velocity variations (also written on table 3) are too high (≈ 20 kms) to be caused by an orbiting exoplanet. From this I assume the object is the spectral binary like HD 99458. Radial velocities were determined with the same method as mentioned higher. For HD 210803 I used only 7 intervals, since the interval between 400 nm and 425 nm has too low signal to noise ratio.

For better system characterisation and more accurate results I will continue in observing the star to take the images at missing phases.

Phase	RV [km/s]	σ [km/s]	Phase	RV [km/s]	σ [km/s]
0,314	0,1	1,0	0,048	7,2	1,8
0,322	-2,0	2,6	0,052	11,0	1,2
0,334	-0,1	1,4	0,056	10,0	1,6
0,971	20,8	1,6	0,060	6,3	1,2
0,976	20,0	1,4	0,144	3,77	0,58
0,980	19,1	1,4	0,148	3,23	0,83
0,281	-0,98	0,43	0,152	3,48	0,78
0,289	0	0	0,157	2,48	0,68

Table 3. Radial-velocity measurements for HD 210803.

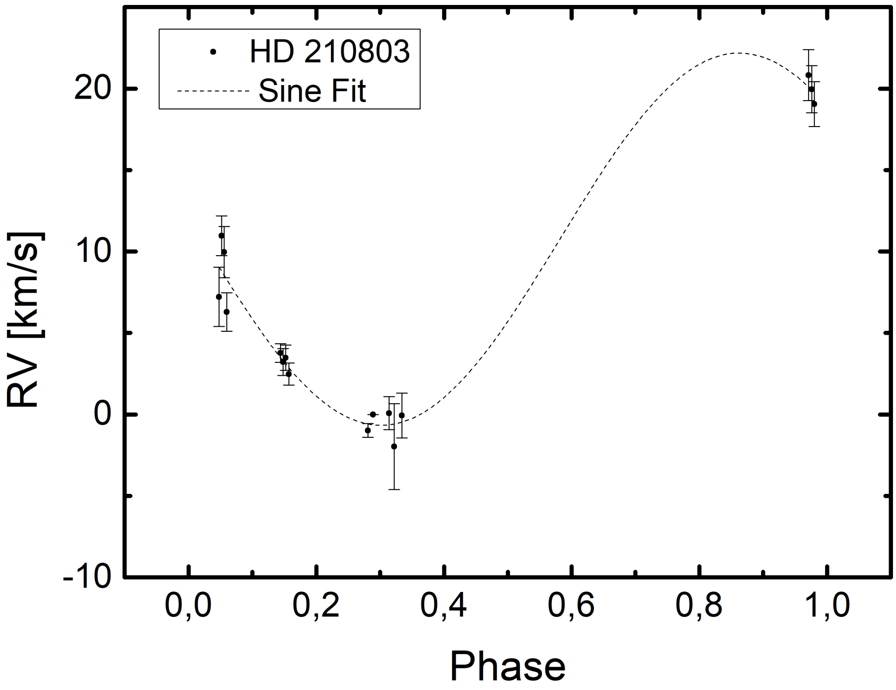

Figure 9. Phase diagram of HD 210803 radial-velocity measurements.

6.3 HD 23765

HD 23765 was observed for 8 nights and in sum 19 images were taken and processed. However many images have too low signal to noise ratio. Fit of crosscorelation function did not converge at the interval 450 nm - 550 nm for most of the pictures. I got the same results at small intervals as the fit did not converge because of low signal to noise ratio.

I tried to fit the location around Hα and sodium doublet. These lines are the most significant in the final spectrum. Results were similar as the fit did not converge or it was too inaccurate. I was changing the parameters of fit but the results put into the phase diagram were wrong. They did not show any periodic variations as the values were so inaccurate.

There is also another problem with the data. A visible gap is inside of all significant spectral lines in the final spectrum. Lines look like they are divided in the middle. This can be a sign of spectral binary star. For more accurate results I will have to observe the star again and try to increase S/N. Also fitting the crosscorelation function for every single (significant) line could help to determine the radial velocities.

With respect to these results I can conclude HD 23765 is a spectroscopic binary (Lehman H. [11]). Fitting methods of single lines to obtain RVs for spectral binaries will be performed as described e.g.

Radial velocities determined for this star are on the table 4. A value of standard deviation is derived from task fxcor. Example of spectral line (Hα) with divided shape is shown in the figure 11 and it can be compared with usual Hα line in the figure 10.

Phase	RV$_{H\alpha}$ [km/s]	σ [km/s]	Phase	RV$_{Na-doublet}$ [km/s]	σ [km/s]
0,238	-1,03	—	0,238	0,77	0,23
0,197	0,9	1,2	0,197	4,29	0,76
0,203	7,0	1,3	0,203	6,86	0,98
0,216	23,5	1,6	0,210	9,6	1,0
0,791	0,00	0,00	0,791	0,00	0,00
0,803	-1,83	0,30	0,803	5,34	0,81
0,392	-5,3	3,0	0,392	-0,42	0,27
0,399	-1,5	4,6	0,399	1,64	0,30
0,405	0,9	3,5	0,405	0,71	0,28
0,553	0,9	3,6	0,412	0,54	0,31
0,566	1,3	4,1	0,553	2,13	0,34
0,817	5,2	1,7	0,566	2,61	0,31
0,782	12,82	0,98	0,817	8,13	0,88
0,831	3,0	1,9	0,782	3,65	0,70
0,843	3,7	2,6	0,789	3,26	0,72
0,856	4,2	1,8			

Table 4. Radial-velocity measurements for HD 23765. Values on the left correspond with the measurements at Hα position, values on the right with sodium doublet.

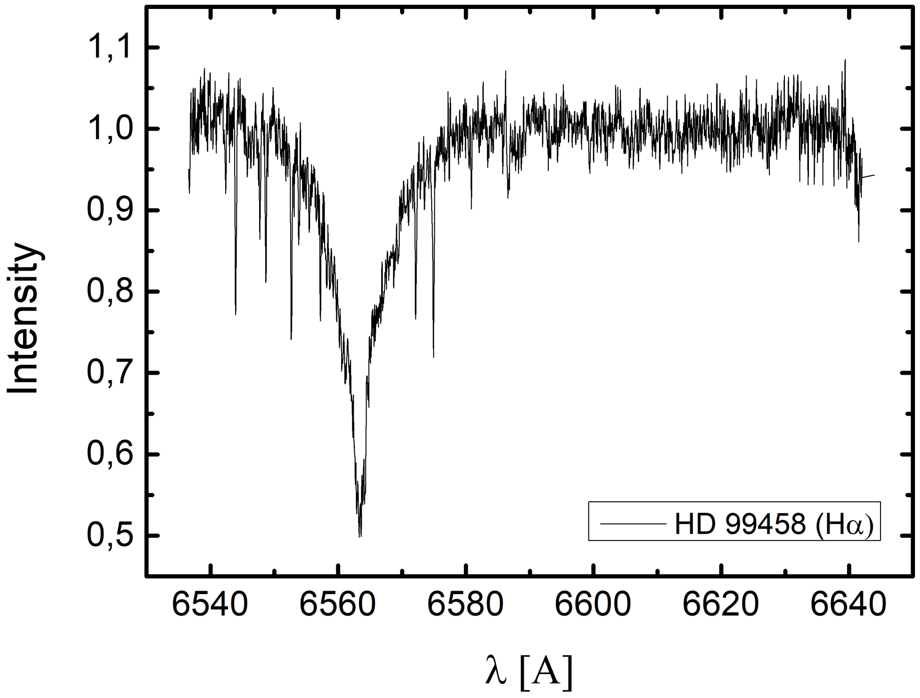

Figure 10. Hα line in spectrum of HD 99458.

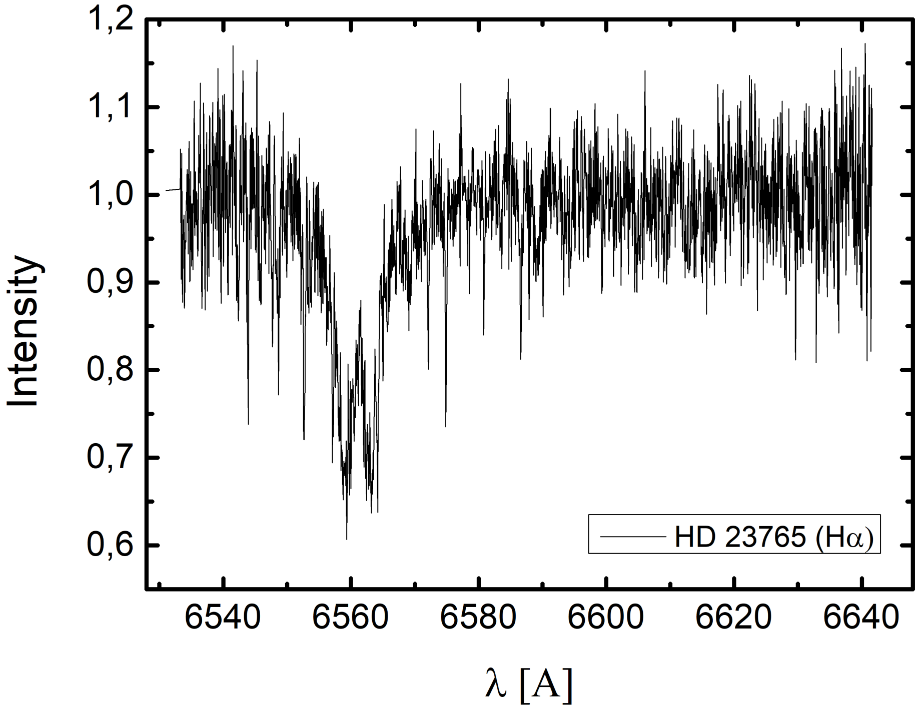

Figure 11. Hα line in spectrum of HD 23765. The line splits in the middle.

7 Summary

While working on this project I have learned the process of observing the chosen targets, processing the data and their analysing. Three targets where chosen for observations. For two stars - HD 99458 and HD 210803 - radial velocities where obtained from the data. For given results it is significant that radial-velocity variations are too high to be caused by the exoplnet so both stars are eclipsing binaries. Further analysis will determine the basic parameters for both stars. The result spectra of HD 23765, especially the shape of Balmer spectral lines which are divided in the middle, indicates it can be also an eclipsing binary star. Further analysis will be needed to prove this hypothesis. Radial velocities of HD 23765 can be obtained using single lines fitting in the star spectrum. Results of this project confirm the sufficient level of accuracy of OES spectrograph at Ondřejov observatory of Astronomical Institute of the Czech Academy of Sciences for spectral typing and excluding of false positive such as spectroscopic binaries etc.

8 References

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