The observation of exoplanet 51 Pegasi b

by Christian Buil

This page presents an observation result of the extrasolar planet 51 Pegasus b with a small telescope. The planet in question revolves around the star system Pegasus. This is the first object of this type detected in 1995 by the method of radial velocities by Michel Mayor and Didier Queloz with the ELODIE spectrograph installed on the 1.93 m telescope of the Haute-Provence Observatory.

This is for me a revisit. I had already highlighted 51 Peg b in 2009 using an eShel spectrograph (Shelyak Instruments), which displays a resolving power of R = 10000. See the record of this observation here . The observation is very delicate because the radial velocity variation printed by the planet at the star is only +/- 56 meters per second (the orbital period of 51 Peg b around the center of mass of the system is 4.3 days).

To give an idea of the difficulty, let us recall the Doppler-Fizeau formula which links the radial velocity of the object Vr (projected along the line of sight) and the displacement of the spectral lines Dl :

$$V_{\mathrm{R}} = c \ \frac{\lambda_m - \lambda_0}{\lambda_0} = c \ \frac{\Delta\lambda}{\lambda_0}$$

with *c* , the speed of light, l_0 length when the object is at rest and l_m the wavelength when the object moves.

By making c = 300000 km / s and Vr = 0.056 km / s for the case of 51 Pegasus, it is easy to find that the displacement Dl of the spectral lines due to the presence of the planet is only +/- 0.001 angstrom relative to at the idle position, which is tiny (1/100 pixel typically in the spectrum image). We understand why the detection of the first extrasolar planets is a relatively recent discovery, even with the means available to professional astronomers.

I show in this page that the study of exoplanets, the confirmation of their presence (for example in the context of the future PLATO space mission), or even their discovery, becomes a possible activity for amateurs if the objects targeted are relatively brilliant. I recall that the visual magnitude of 51 Pegasus is 5.5.

Let's look at the star Pegasus as seen from the Earth and study how its radial velocity evolves over a period of one year. Figure 1 gives the result, with the X axis in days, and the Y axis the apparent speed of the star in meters per second.

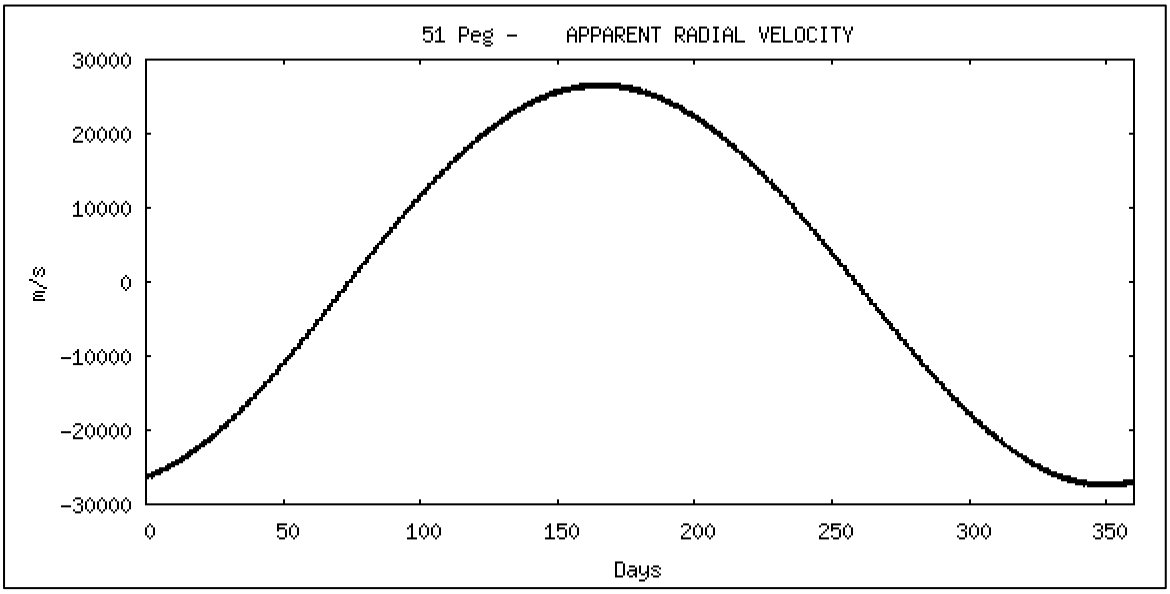

Figure 1. Modelling the apparent radial velocity of the Pegasus star 51 over a year of time

This speed can be deduced from the displacement of the lines in the spectrum (Doppler-Fizeau effect). This is a very accurate mathematical modeling of reality.

A cycle of one year is clearly shown with an amplitude of +/- 27 km / s. It is of course synchronous with the orbital motion of the Earth. The explanation is in Figure 2.

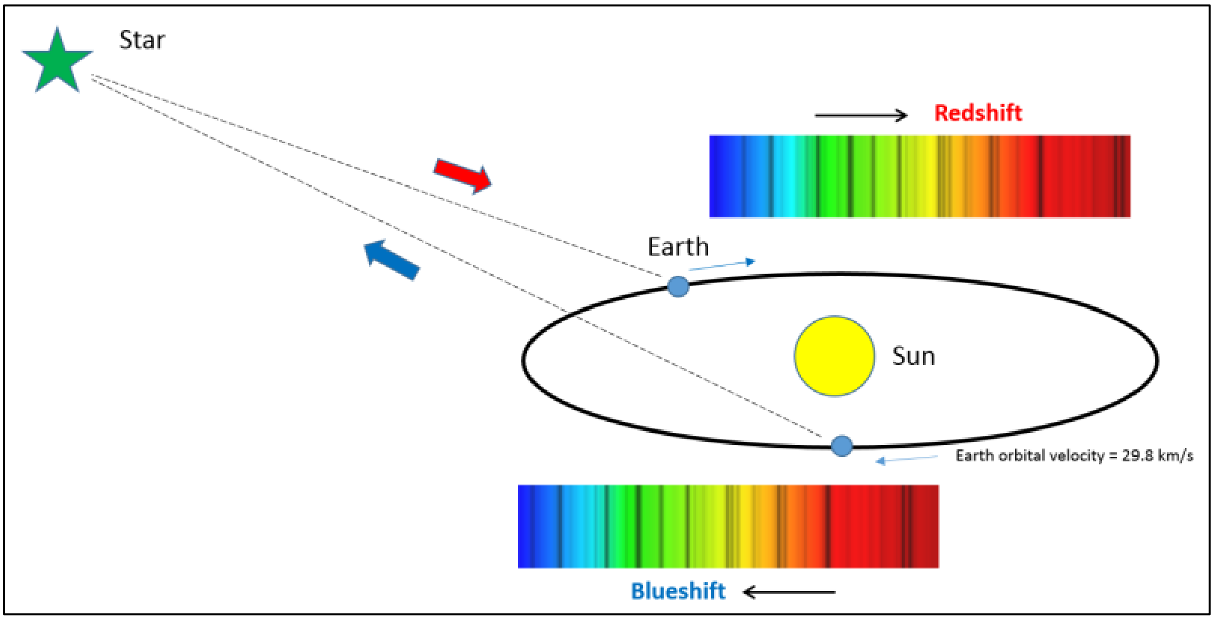

Figure 2. Motion of the Earth relative to the star

Depending on whether the observer, due to the movement of the Earth around the Sun, approaches or moves away from the star, the spectral lines are shifted either to blue or to red. The average orbital speed of the Earth is about 30 km / s. The star 51 Peg being close to the orbital plane of the Earth (close to the ecliptic in the sky), the annual movement of the lines corresponds to a radial velocity of the order of +/- 30 km / s.

We recall that the Doppler-Fizeau effect induced by the exoplanet is only 0.056 km / s, compared with the simple fact that the orbital speed of the Earth induces an effect of 30 km / s. At the scale of Figure 1, the presence of the planet is of course invisible.

But let's take a closer look at Figure 1 by magnifying it. This is shown in Figure 2.

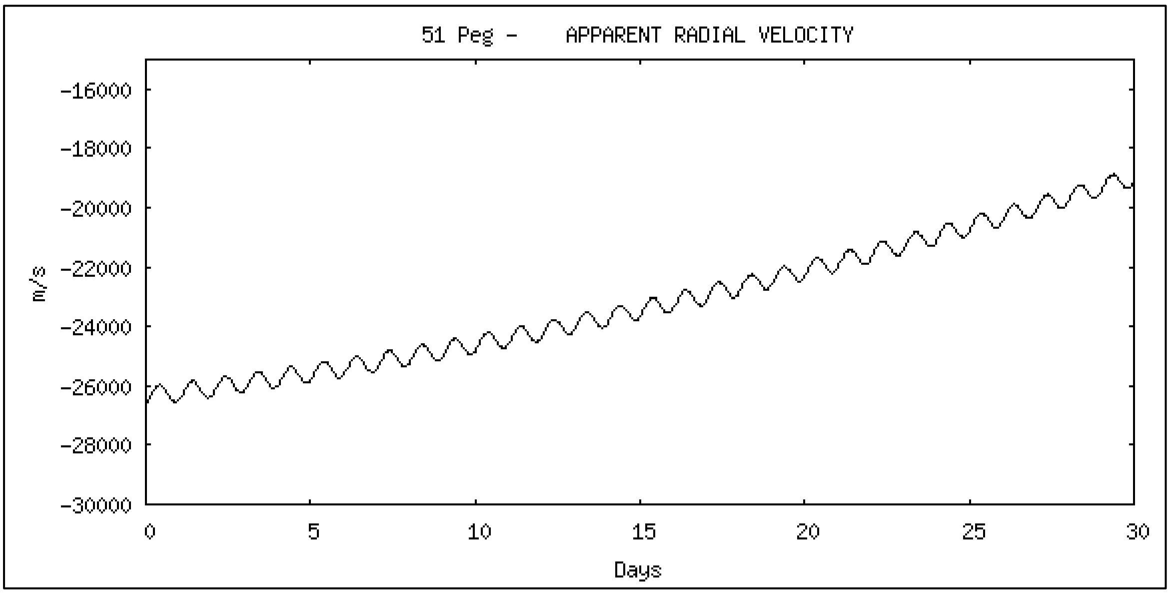

Figure 2. The variation of the apparent radial velocity of star 51 Peg over a period of 30 days.

Periodic oscillations appear of relatively small amplitudes. The time difference between two successive maximums or two successive maximums and minimums is precisely equal to 24 hours. This is the diurnal rotation period of the earth around its axis.

The 24-hour oscillation found in Figure 2 corresponds to the radial motion of the observatory due to the daily rotation of the Earth (depending on whether the Earth is approaching or moving away from the star). In Figure 3, the amplitude of this diurnal radial velocity is better highlighted after removing the annual component.

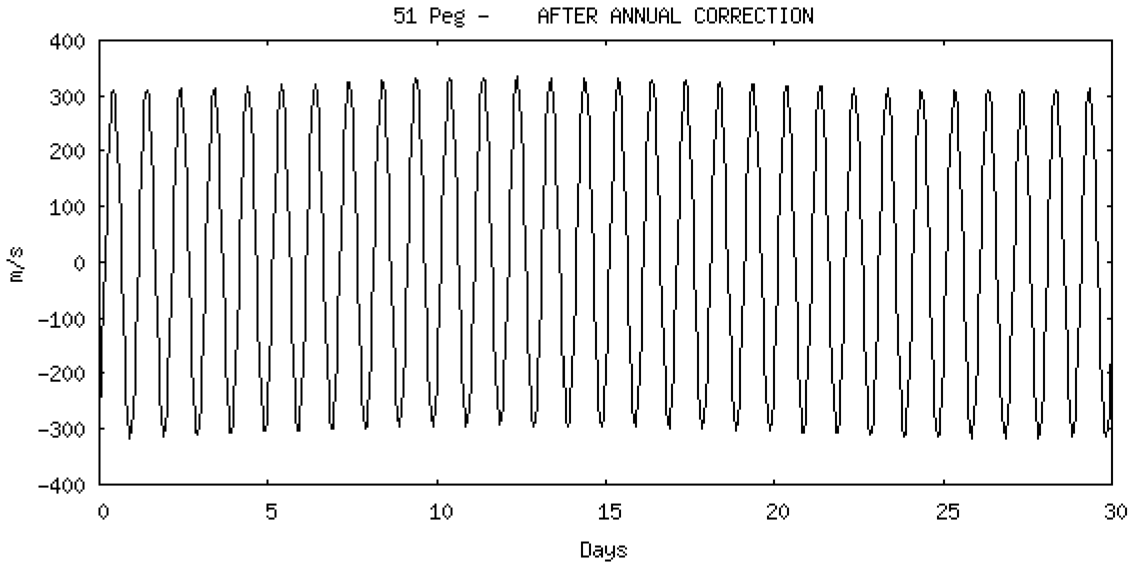

Figure 3. Radial apparent velocity detail of 51 Peg after removing the annual component.

In the situation of the observation of the star Peg 51 and given its position in the sky, the amplitude of variation of the radial velocity related to the diurnal rotation is +/- 300 m / s, (compare to the effect of 51 Peg b on its host star that one seeks to detect, i.e. +/- 56 m / s).

An attentive eye will see in Figure 3 that the average speed of the star varies very slightly over the 30-day period. The reason is that the centre of the Earth revolves around the centre of gravity of the Earth-Moon system in about 27 days. The result is a subtle back-and-forth motion of the observer, called lunar radial motion.

In Figure 4, the diurnal speed component of the Earth has been removed (the effect is perfectly deterministic). There remains only the disturbance induced by the Moon.

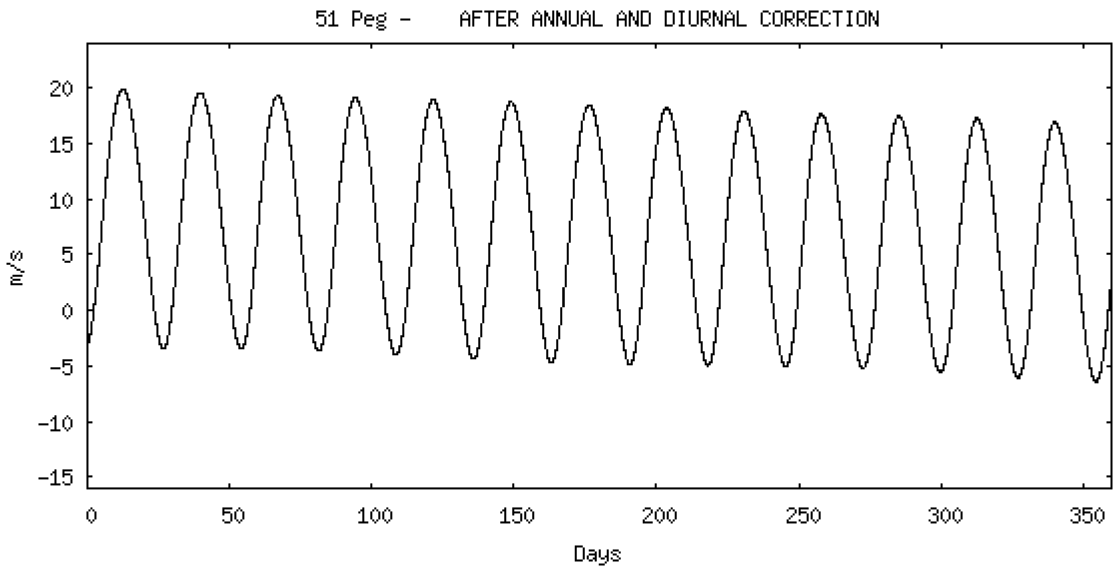

Figure 4. Monthly variation in the radial velocity of star 51 Peg due to lunar attraction. The total amplitude is 25 m / s.

The amplitude of the radial velocity caused by the Moon on Earth is of the same order of magnitude as the effect of exoplanet 51 Peg b on its host star. It must also be removed from the observations to extract the actual radial velocity of the 51 Peg system. Figure 5 shows the result of the operation.

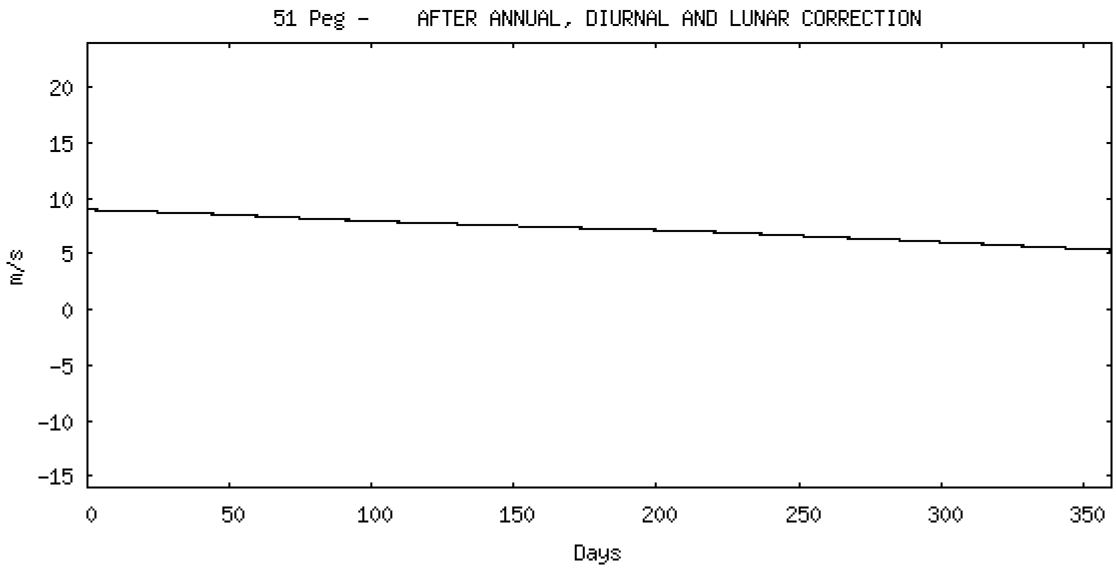

Figure 5. 51 Peg residual velocity after removal of the Moon's effect on Earth's motion.

There is a slow gradient of 5 m / s over the year. This time the centre of mass of the solar system is concerned.

The slow residual variation observed over the year indicates that the Earth does not rotate with respect to the center of the Sun, but with respect to the barycenter of the system constituted of the Sun and the planets (Jupiter, Saturn, ...). The barycentric point is actually close to the surface of the Sun, with a large influence of the planet Jupiter. The modelled variation in Figure 5 is in fact a part of a sinusoidal period of about 11 years, corresponding to the orbital period of Jupiter around the Sun. Viewed from 51 Pegasus, the Sun rotates around the center of mass of the global planetary system with an amplitude of 12 m / s (the influence of the Earth is only 9 cm / s).

If the velocity of the observer is related to the sun, it is called heliocentric. Ideally, it is necessary to reference the speed relative to the centroid (barycentric center) of the solar system. The result of the apparent variation in the radial velocity of the star is shown in Figure 6.

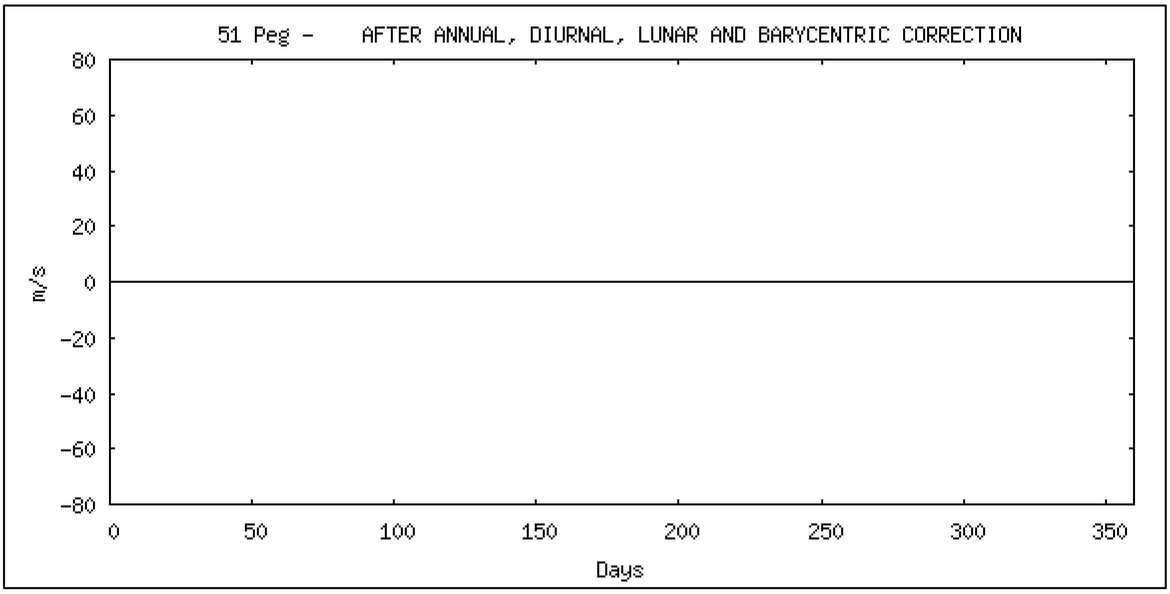

Figure 6. 51 radial velocity after full barycentric correction.

In fact, the residual velocity is never zero. The systemic velocity of the star is present, but it is constant over time, and therefore, it can be ignored.

The ISIS software has a tool that returns the heliocentric and barycentric radial velocity correction to be applied when observing a given star (the coordinates of the star are in the J2000 system). You must first indicate in the "Configuration" tab the geographic coordinates of the observatory. Figures 7 and 8 show a concrete example. The precision of the model implemented in ISIS (VSOP87 theory) is 1 to 2 m / s, which is excellent.

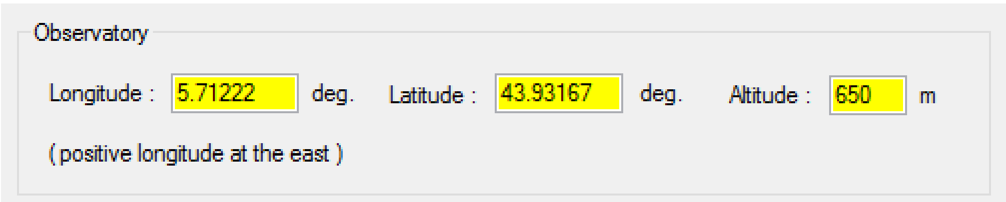

Figure 7. Geographical coordinates of the observation point, here those of the Observatory of Haute-Provence (south of France).

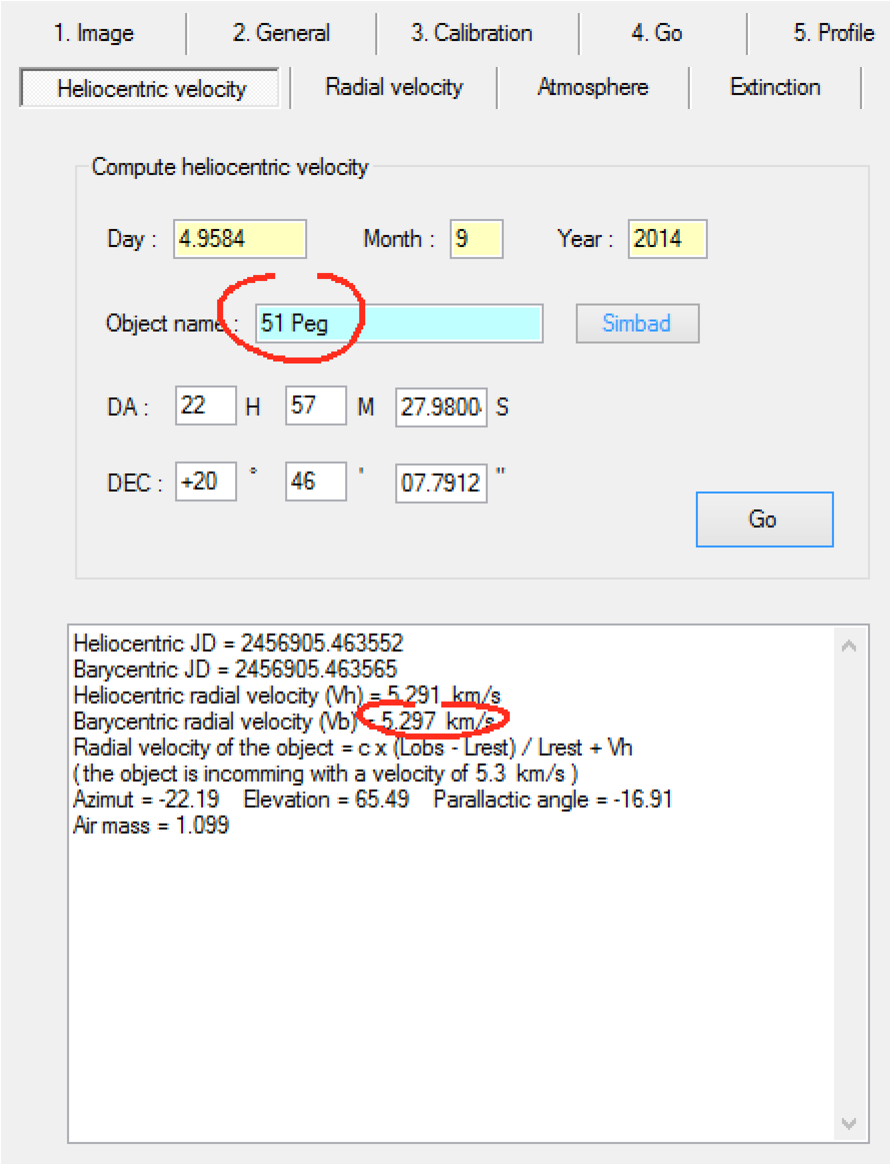

Figure 8. Example of calculation of the barycentric speed of the Earth against 51 Pegasus with ISIS. The date is in Universal Time. Here, the observer and 51 Pegasus go towards each other at a speed of 5.297 km / s.

Let us come to the actual observation of 51 Pegasus. For this study, the measurement period runs from the end of July 2014 to the beginning of September 2014. At the end of July, the observations took place at the OHP during the annual spectrography workshop (ARAS, AUDE). The telescope used was then a Celestron 9 (D = 0.235 m). The rest of the time, observations were made from my personal observatory Castanet-Tolosan (France) with a Celestron 11 telescope (D = 0.28 m).

I used the VHIRES-MO spectrograph (Multi-Order version), which is for the most part a personal achievement. It is a scale spectrograph in the most stripped form, with a resolving power (R) of 50000. It operates in quasi Littrow, with a double passage in the cross dispersive element (cross-disperser).

The spectrograph is equipped with a small CCD camera, but powerful thanks to its low noise reading (Atik 460EX). A major technical choice of this spectrograph consisted in aiming for a generous dispersion, with a spectral sampling of 4 pixels per FWHM, and of course, it was noted, a very high power of spectral resolution (R = 50000). The objective of the spectrograph is a very good dioptric optics with a very generous image field (Takahashi astrologer FSQ-85ED, apochromatic, focal length = 450 mm, f / 5.6).

The array is a Richardson scale model, 220 x 110 x 30 mm, with an engraving density of 110 lines / mm and a blaze angle of 64.5 °. It is the major optical part of the system (with the quality of the telescope, whose image quality is limited by diffraction over the entire spectral domain explored).

The cross-dispersive element is a prism with 7 ° apex angle and 80 mm diameter (the objective of the FSQ-85ED bezel is slightly diaphragmed by this element).

The telescope and the spectrograph are connected by a fiber of 50 microns diameter and 10 meters long. A second 500 micron diameter fiber brings the calibration flow to the telescope-mounted lens (I use a Thorium-Argon lamp for spectral calibration (SHELYAK Instrument system) and tungsten lamp for gain calibration and order tracking).

The diffraction orders are truncated by the small size of the detector and the choice of a long focal lens, so that only 1/6 of the exploitable spectral range is ultimately captured. FIG. 9 shows the image of the spectrum of the star 51 Peg, with the indication of the spectral limits actually useful per order

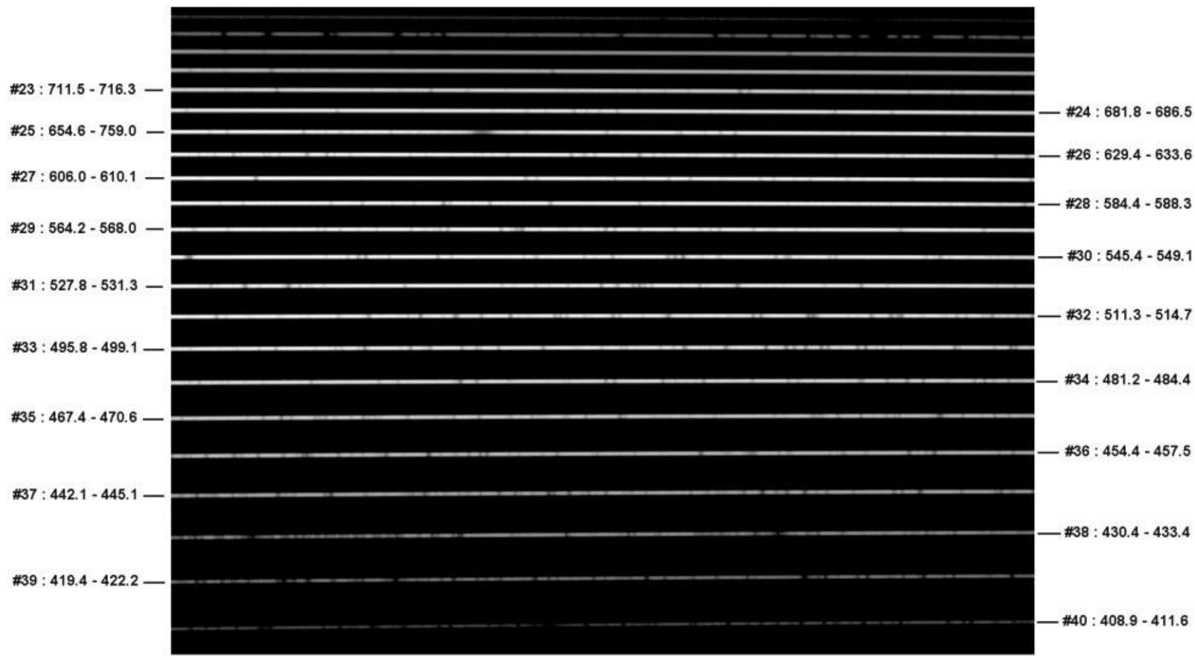

Figure 9. 2D image of the star spectrum 51 Peg.

The spectral window of each order is indicated (in nanometers), as well as the number of the order (#xx). For example, the spectral order 35 covers a spectral range from 4674 A to 4706 A.

The spectral sampling at 5500 A is 0.0268 A per pixel. The overall performance of the instrumental chain (including the atmosphere with a star at the zenith and also taking into account the CCD camera) is 5.7%. This is the ratio of the number of photoelectrons produced by the number of incident photons. This yield is 4.5% at 6850 A and 1.2% at 4200 A.

An optimal processing pipeline of the VHIRES-MO spectra was written in ISIS (V5.5). A spectral option extracts the CCF (Cross-Correlation Function and the radial velocity. The CCF mask has 225 carefully selected spectral lines (Figure 10).

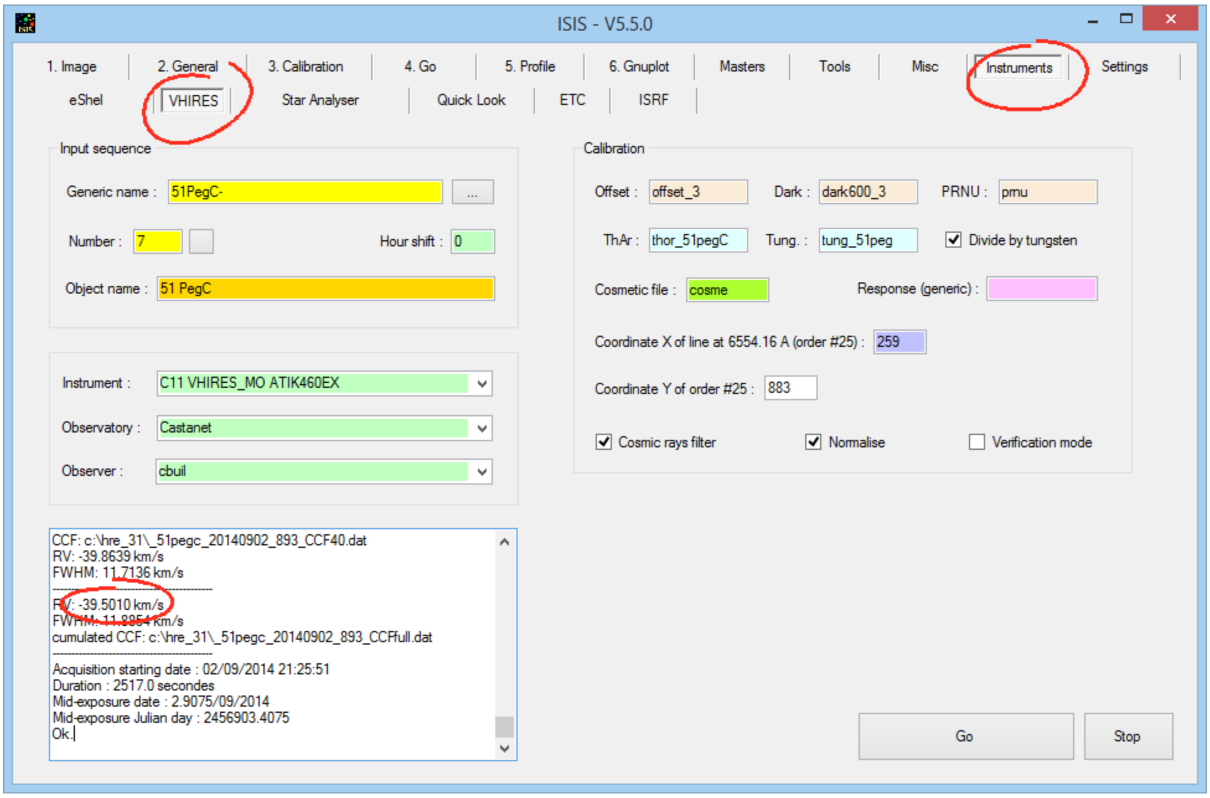

Figure 10. Special window for processing VHIRES-MO spectra in ISIS software. The processing is very automated

An experimental statistical study leads to the following relationship between the signal-to-noise ratio measured in the continuum in green and the radial velocity accuracy at 1 sigma:

$$\sigma_{\mathrm{RV}} \simeq \frac{1,50 \times 10^3}{(S/N)_{\mathrm{FWHM}}} = \frac{740}{(S/N)_{\mathrm{pixel}}} \quad (\mathrm{m/s})$$

For the star Pegasi 52, depending on the telescope and the exposure time, the typical signal-to-noise ratio per pixel during the observation is between 100 and 200, a measurement error expected on this star between about + / -20 m / s and +/- 10 m / s at 3 sigma.

Figure 11. Aspect of VHIRES-MO spectrograph in test phase at the Midi Observatory on the 60 cm telescope (July 2014). The orange optical fiber conduct the star light to the spectrograph.

Figure 12. The wide scale grating (grade tilt angle) and the cross-scatter in front of FSQ-85ED objective lens.

Figure 13. The fiber optic injection flow principle into refractor (off-axis system). In the background is the CCD detector surface.

Figure 14. The observation site from the Haute-Provence Observatory.
The telescope is placed outside the 120 cm telescope dome.
The spectrograph is installed in a laboratory attached to the same telescope. Photo Olivier Garde.

Figure 16. Installation of the spectrograph at the OHP. In the foreground is the Thorium-Argon lamp.

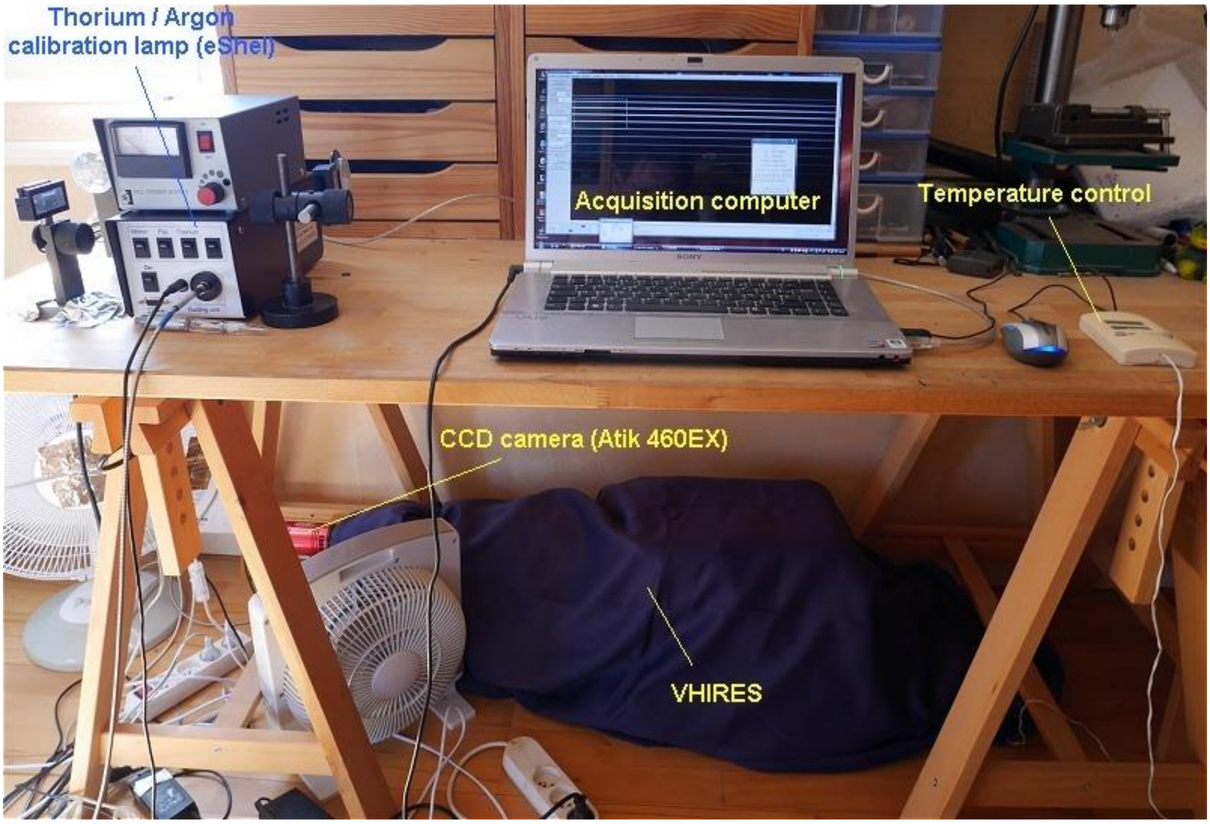

Figure 17. The spectrograph at the Castanet-Tolosan Observatory.

Figure 18. When shooting, the optical fiber is constantly moved laterally with a large amplitude (with a frequency of about 0.1 Hz) by the pivot movement produced by simple fans (an improvised and provisional solution, but nevertheless effective!). I use a set of 4 oscillating fans distributed along the length of the fiber to eliminate the modal spectral noise and also surely, by the effect of jamming, to standardize the stellar image at the output fiber (near field), a key solution to improve radial velocity accuracy measurement.

Figure 19. The fiber interface and guiding system coupled to the Castanet-Tolosan C11 telescope. This setup is from SHELYAK Instrument - a part of eShel spectrograph - easy to use and very efficient. The guiding camera is a Atik314L + model.

Let's come to the result of the study. Figure 20 shows the radial velocity of 51 Pegasi measured as a function of time in the barycentric reference system of the solar system (see above all the numerical corrections to be made).

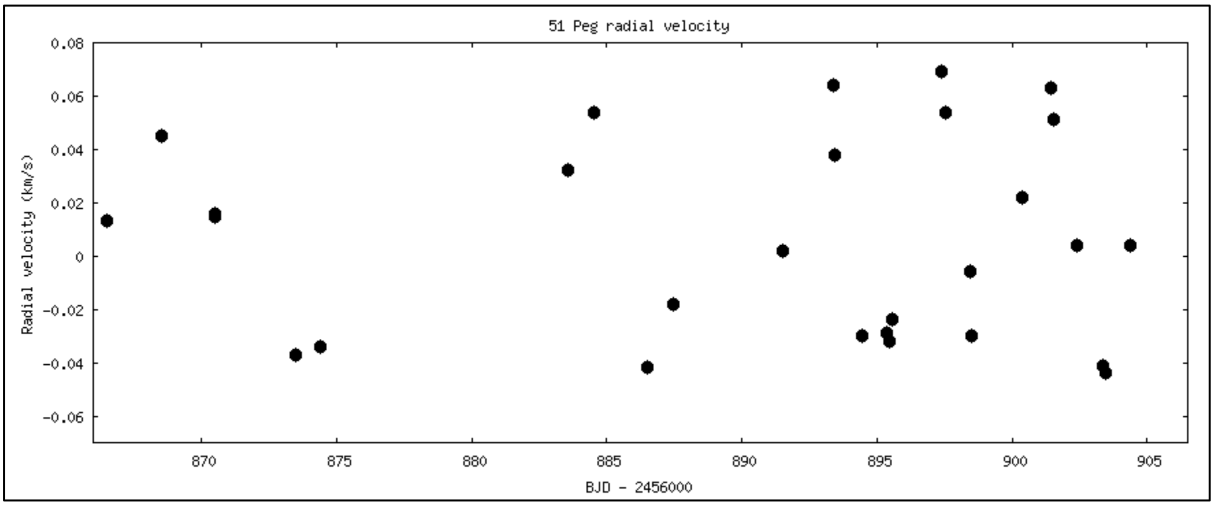

Figure 20. Radial velocity after barycentric velocity correction and after removal of the star systemic speed, taken equal to -33.129 km/s.

The left point group corresponds to measurements made at the Observatoire de Haute-Provence (C9 telescope), the right point group is Castanet-Tolosan observatory (C11 telescope). Measuring points appear strongly scattered around the zero speed ... We are far from observing the beautiful straight line of Figure 6! Is it measurement noise? Let's do a periodic analysis of this signal (calculation of the periodogram, it is tool is available in ISIS). The result is shown in Figure 21.

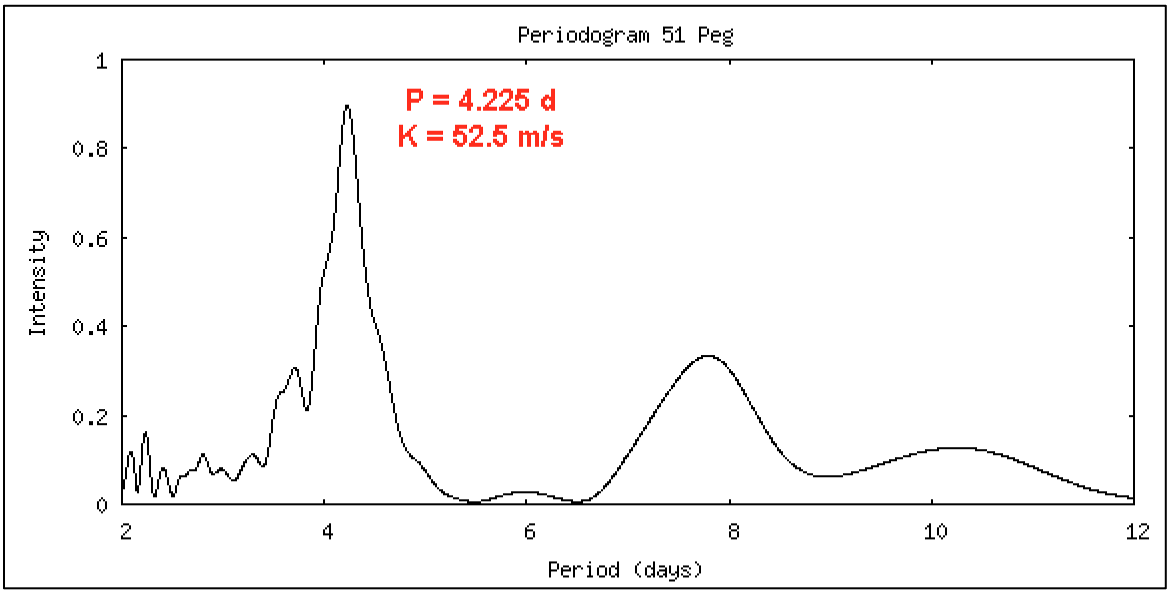

Figure 21. Periodogram of measurements of 51 Peg (Lomb-Scragle algorithm).

Period (P) appears to be 4,225 days. In addition the adjusted model gives a half amplitude (K) of 52 m / s. The known values for the 51 Peg system are P = 4,231 days and K = 56 m / s. The measured data are therefore very close to the expected values. The presence of planet 51 Peg b is clearly detected. The existence of 51 Peg b is confirmed by this analysis. Figure 22 shows both the points measured as a function of time and the calculated radial velocity model. The situation becomes clearer: the dots draw approximately the radial movement of the star!

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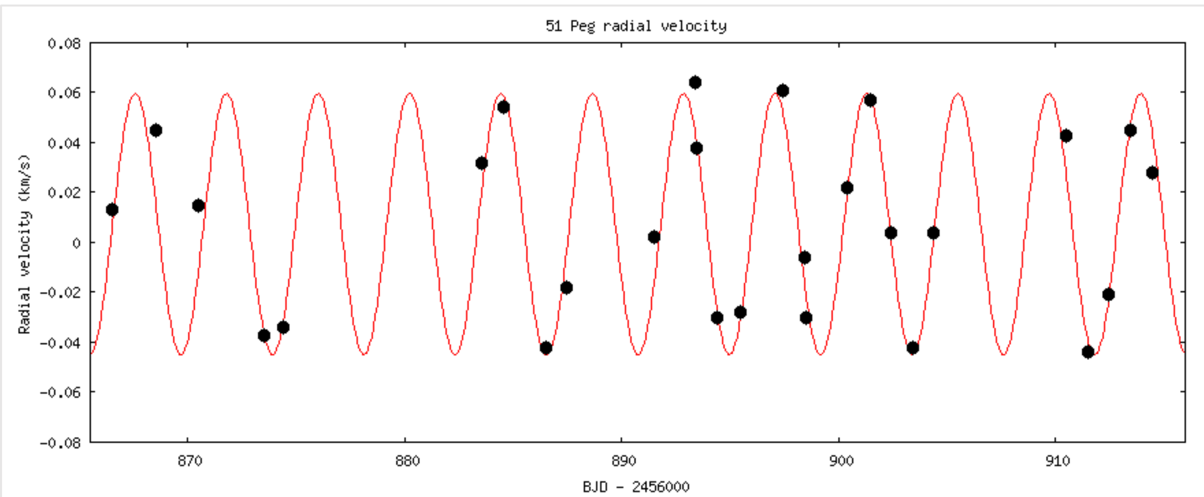

Figure 22. Measured points and models calculated for the 51 Peg system (July to September 2014).

The figure 23 is the phase curve where all measurements are reduced over the same period (here 4.225 days).

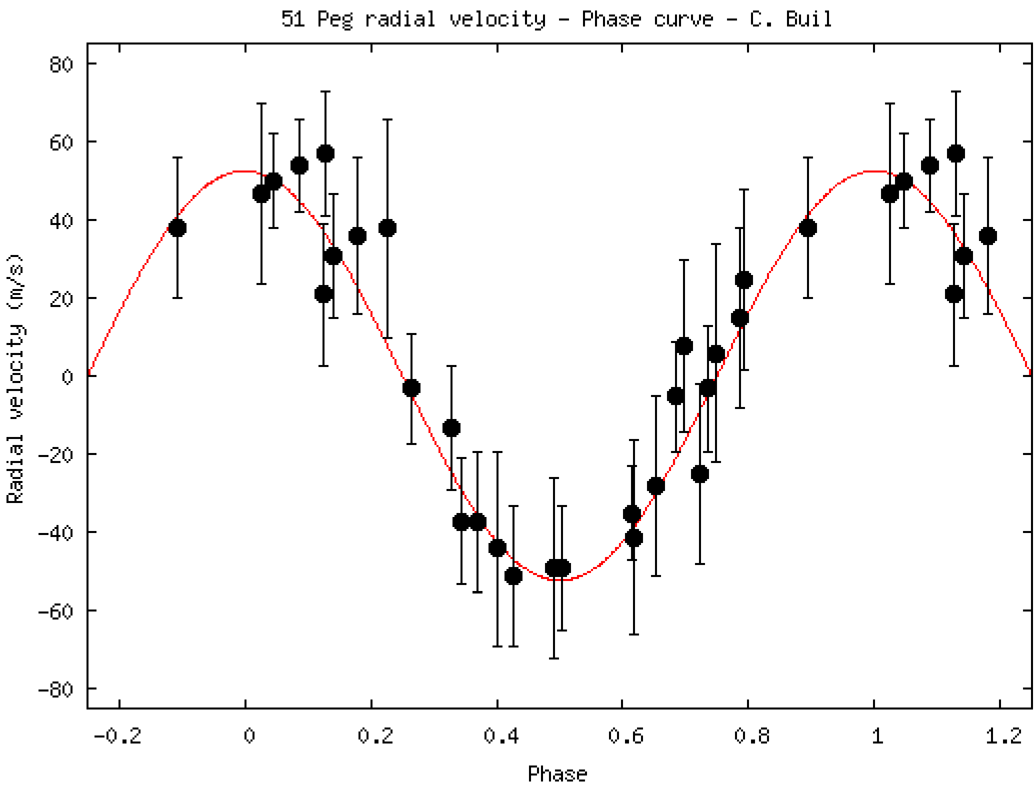

Figure 23. Final phase curve of the radial velocity of 51 Pegasus. The error bars are at 3 sigma. Data acquired from July to September 2014.

The measurement error at 3 sigma for this session dedicated to 51 Peg is evaluated between +/- 12 m / s and +/- 24 m / s (depending on the display, the exposure time, ...). It should be noted that the coherence over a long time is very good, even though the spectrograph was completely dismounted between two measurement sessions (OHP episode and Castanet episode). It is recalled that the movement of the lines relative to the orbital period of 51 Peg b is minute, well below the size of the detector pixels, imperceptible to the eye when the spectrums are superimposed.

Only by using a powerful correlation technique (CCF) involving a large set of spectral details does the radial motion become noticeable. It is also necessary to follow a binding calibration protocol, but rigorous (many measurements interposed on the Thorium-Argon lamp).

The typical Cross-Correlation Curve is presented in Figure 24.

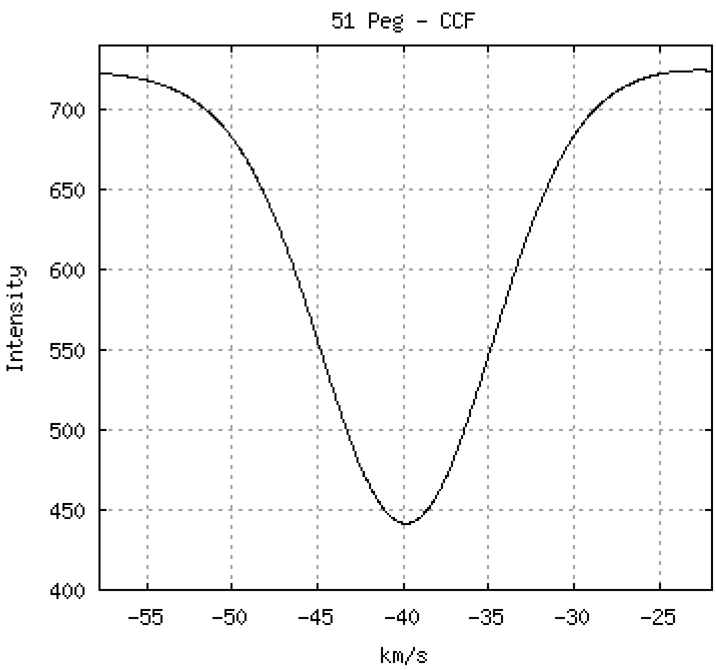

Figure 24. Typical Cross-Correlation Function (CCF) of the Star 51 Peg spectrum, calculated from 225 carefully selected spectral lines by hand.

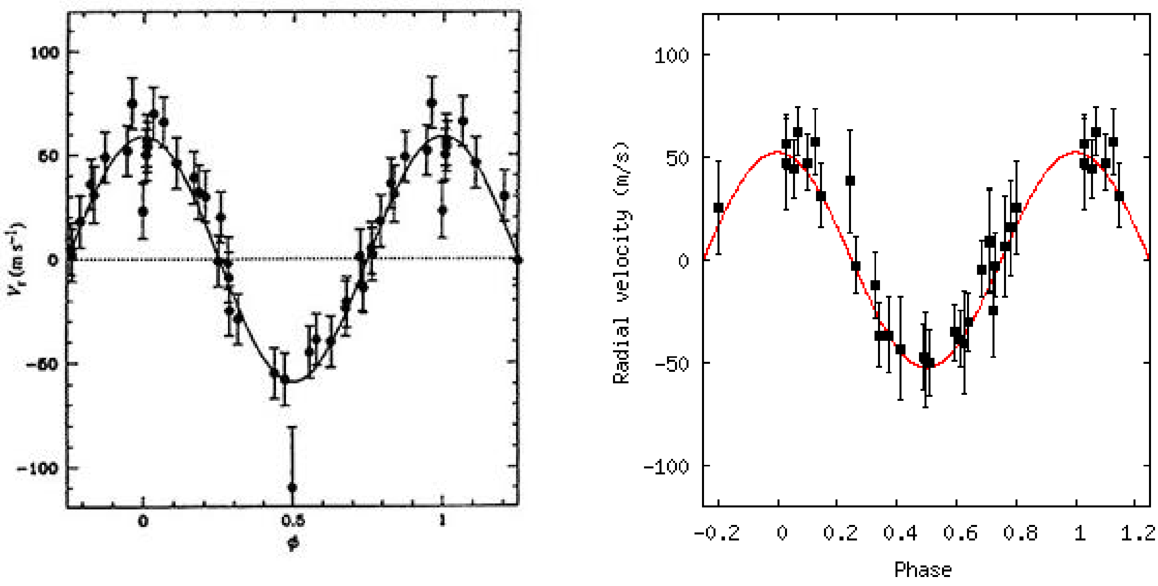

Figure 25. On the left, the original work of Mayor and Queloz published in 1995 in the journal Nature (ELODIE spectrograph on the 1.93 m telescope of the Haute-Provence Observatory). On the right, the result of the study presented in this page (VHIRES spectrograph, telescopes of 0.23 m and 0.28 m).

The detection of the presence of a hot Jupiter, such as that which revolves around the star 51 Peg, is today relatively easy with amateur means. Since 1999, the date of my first observation of 51 Peg, the material has made progress, the spectral processing procedures are refined and the benefit of the experiment does the rest.

With a 28 cm telescope and a spectrograph of the class of a VHIRES, we can expect to achieve an accuracy of about 10 m / s on stars brighter than magnitude 4. This same level of accuracy is achievable with a good telescope 40 to 50 cm in diameter up to magnitude 6.5 at least. Note that at this level, the main limitations come from the noise caused by the optical fiber, thermal deformations of the spectrograph, ...

The scope is considerable. With such a potential and thanks to the multiplicity of measures (especially if the work is organized and collaborative) the amateurs can become credible actors to confirm many extrasolar planets revealed by the method of occultations during the future programs of terrestrial and spatial observations. The astroseismological study of the stars is also an area in which it is possible to trace its groove. The adventure of spectrography among amateurs is just beginning!

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