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Extrasolar planets and brown dwarfs around A–F type stars⋆

III. β Pictoris: looking for planets, finding pulsations

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ABSTRACT

In the frame of the search for extrasolar planets and brown dwarfs around early-type stars, we present the results obtained on β Pictoris, which is surrounded by a circumstellar disk that is warped by the presence of a planet. We used 97 spectra acquired with CORALIE and 230 spectra acquired with HARPS to characterize the radial velocity behavior of β Pictoris and to infer constraints on the presence of a planet close to this star. With these data, we were able to exclude the presence of an inner giant planet (2 $M_{\rm Jup}$ at a distance to the star of 0.05 AU, 9 $M_{\rm Jup}$ at 1 AU). We also discuss the origin of the observed radial velocity variations in terms of δ Scuti type pulsations.

Key words. techniques: radial velocities – stars: early-type – stars: variables: δ Sct – stars: individual: β Pictoris

1. Introduction

β Pictoris (A5V, 19 pcs, Crifo et al. 1997, ≈20 Myr, Barrado y Navascues et al. 1999) has been the subject of intensive investigations since the first discovery of an extended (≥100 AUs) circumstellar disk (Smith & Terrile 1984) and since evidence that the lifetime of the grains in the disk was significantly shorter than the star age. It was then deduced that some grains were permanently formed through collisions among larger, possibly kilometer sized bodies, or perhaps by slow evaporation – at least partly (see Lecavelier Des Etangs et al. 1996). The β Pictoris disk was then considered as the first example of a resolved outer planetary system in a still unkown stage of evolution. Given the star age, it was possible that planets could be already formed or still under formation. Observation of a warp in the inner part of the disk was attributed to gravitational perturbation of the disk by a giant planet whose location could be constrained (Mouillet et al. 1997; Augereau et al. 2001, and references therein). Besides, episodes of strong and rapid infalls of ionized gas were detected and attributed to the evaporation of cometary objects grazing the star (Ferlet et al. 1987; Lagrange et al. 1988; Beust et al. 1990). Again, one or two giant planets within a few AUs were found to be necessary to trigger this infall of cometary bodies towards the star (Beust & Morbidelli 1996, 2000,). Finally, photometric variations were also detected once and possibly (but no exclusively) attributed to the presence of a planet passing the line of sight (Lecavelier Des Etangs et al. 1995, 1997). For a review of these possible pieces of evidence, see e.g. Vidal-Majar et al. (1998) or Lagrange et al. (2000).

Direct detection of planets within a few AUs of a star aged 20 Myr or more is beyond the capability of current instrumentations. On the other hand, indirect detection through, e.g., radial velocity searches have been restricted to solar type stars until recently. Given the interest in understanding the planet formation process over a wide range of stellar characteristics and especially for massive stars, we set up a radial velocity survey dedicated to the search for planets around A–F type stars, using a dedicated analysis package that allows detection of companions down to planetary masses around such objects (Galland et al. 2005a, Paper I). Here, we present the results of a radial velocity survey of β Pictoris with CORALIE and HARPS performed over a period of several months. The data and the radial velocities obtained are presented in Sect. 2: the radial velocities are significantly variable. We show in Sect. 3 that these variations cannot be attributed to the presence of a planet. Section 4 explores other possible origins: stellar or cometary related. The origin of the variations finally involves pulsations of δ Scuti type. In Sect. 5, constraints are put on the remaining possible characteristics for a planet around β Pictoris, taking the new constraints presented in this paper into account.

⋆ Based on observations made with the HARPS spectrograph at La Silla Observatory (ESO, Chile), and with the CORALIE spectrograph at La Silla Observatory (Swiss telescope).

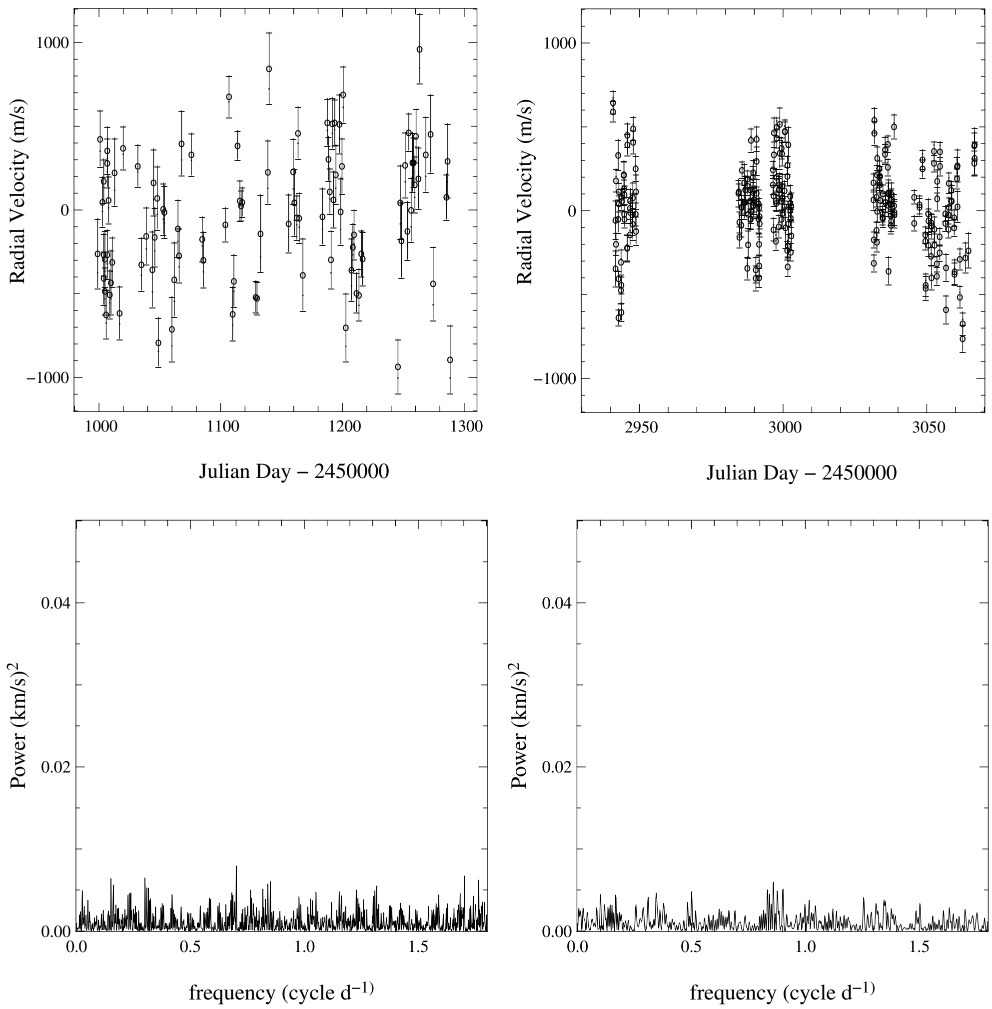

Fig. 1. Radial velocity measurements (*top*) and related periodograms (*bottom*), obtained on β Pictoris using the CORALIE (*left*) and HARPS (*right*) spectrograph. The scale of the periodograms is the same as in Fig. 2; we used the CLEAN algorithm (see text) for these periodograms.

2. Radial velocity measurements

2.1. CORALIE

We acquired 120 spectra of β Pictoris with the CORALIE spectrograph attached to the 1.2 m Swiss telescope at La Silla between July 1998 and April 1999 with a resolution $R \approx 50\,000$. Of these, 23 spectra with significantly lower *S/N* were rejected. We then considered the 97 spectra left with a mean *S/N* of 120. Each spectrum is composed of 68 spectral orders covering the wavelength range 3900 Å to 6800 Å.

For each spectrum, we selected 32 spectral orders containing deep lines, yet avoiding the strong Ca II and H lines, as well as the orders contaminated by telluric absorption lines. The radial velocities were measured using the method described in Chelli 2000 and in Paper I. They are displayed in Fig. 1 (top, left). The individual uncertainty is 163 m s^{-1} on average.

2.2. HARPS

We acquired 258 spectra of β Pictoris with the HARPS spectrograph during period P73, between November 2003 and March 2004, with a resolution $R \approx 100\,000$. The 29 spectra with lower *S/N* have been left over. We then considered the 229 spectra left, with a mean *S/N* of 330 (exposure time of around 1 min). Each spectrum is formed by 72 spectral orders covering the spectral window [3800 Å, 6900 Å].

We performed the same treatement as for CORALIE and obtained the radial velocities displayed in Fig. 1 (top, right). The individual uncertainty is 65 m s^{-1} on average, which is consistent with the value of 60 m s^{-1} obtained from simulations in Paper I by applying the relation between the radial velocity uncertainties and $v \sin i$ to β Pictoris, with *S/N* values equal to 330.

3. No inner giant planet

In the case of CORALIE, the dispersion of the measured radial velocities is 390 m s^{-1} rms, i.e. a factor 2.4 higher than uncertainties. Radial velocities are thus significantly variable, even if the dispersion is still close to the uncertainties.

The periodogram of the CORALIE radial velocities does not show any clear peak in a period range of 1–300 days (Fig. 1, bottom, left). The observed radial velocity variations are thus not due to the presence of a planet. Note that we used the CLEAN algorithm (Roberts et al. 1987) in order to remove the aliases associated with temporal sampling of the data. This algorithm deconvolves the window function iteratively from the initial "dirty" spectrum to produce the resulting cleaned periodogram; the power obtained at a given frequency is the square of the radial velocity semi-amplitude of the corresponding potential radial velocity periodic variations. Assuming a circular orbit, the data exclude the presence of a planet with a period lying typically between 1 and 600 days (hence a separation between 0.03 and 1.8 AU) and with an induced radial velocity semi-amplitude larger than ≈400 m s^{-1} (Fig. 3).

In the case of HARPS, the dispersion of the measured radial velocities is 252 m s^{-1} rms, i.e. a factor 3.9 higher than uncertainties; so, the radial velocities are really significantly variable. Assuming the same level of radial velocity variations at the time of CORALIE and HARPS observations, this higher factor with HARPS could be explained by its greater stability.

The periodogram of the HARPS radial velocities does not show any clear peak in a period range of 1–180 days (Fig. 1, bottom, right). The observed radial velocity variations are thus not due to the presence of a planet. Assuming a circular orbit, we can exclude the presence of a planet with a period lying typically between 1 and 350 days (hence a separation between 0.03 and 1.2 AU) and with an induced radial velocity semi-amplitude larger than ≈250 m s^{-1} (Fig. 3).

4. Origin of the radial velocity variations

4.1. Ruling out cometary bodies

An origin of the radial velocity variations connected to the presence of the complex circumstellar disk of dust and gas has to be addressed, in particular a connection with the evaporating cometary bodies that have been proposed to explain the strong variations observed for some spectral lines of ionized elements such as Ca II, Fe II, Mg II, Al III (Lagrange et al. 2000).

We first computed the cross-correlation function of each spectrum with a binary mask taking into account only lines that correspond to neutral elements. In this way, we obtained a mean line for these neutral elements, with a better *S/N* than for individual lines. These cross-correlation functions do not show analogous variations to the ionized elements Ca II, Fe II, Mg II, Al III. Hence cometary infall does not produce detectable features (at the level of the cross-correlation functions) in the circumstellar lines of neutral elements.

Moreover, we again computed the radial velocities taking only these lines of neutral elements into account. The radial velocities obtained were the same as previously, given uncertainties; the distribution of the differences between them has a dispersion of 78 m s^{-1}, close to uncertainties. We can then conclude that the radial velocity variations are unlikely to be related to the evaporating cometary bodies.

4.2. Ruling out activity

For active stars, spots on the stellar surface induce radial velocity variations ("jitter"), with a period equal to the star rotation period. The β Pictoris rotation period is about 16 h. The periodogram of the radial velocities obtained with HARPS does not show any peak in this range of frequencies, see Fig. 1 (bottom, right). Moreover, β Pictoris does not show surface abundance anomalies in contrast to Ap stars, which also show spectroscopic peculiarities attributed to magnetic activity (Holweger et al. 1997). Furthermore, these stars are usually slower rotators ($v \sin i \leq 120$ km s^{-1}, with a bulk at 80 km s^{-1}), whereas β Pictoris $v \sin i$ is larger than 120 km s^{-1} (Abt 2000). Activity should thus not be responsible for the variations in the radial velocities.

4.3. Pulsations

Even if our temporal sampling does not allow a detailed analysis of short period variations, the large number of spectra obtained with HARPS allows us to enhance two frequencies characteristic of pulsations: at 47.44 ± 0.01 cycle d^{-1} (period of 30.4 min) and 39.05 ± 0.01 cycle d^{-1} (period of 36.9 min) (Fig. 2, top). The square root of the value of the pics in the periodogram stands for the radial velocity semi-amplitude of the corresponding radial velocity periodic variations: $\sqrt{0.046}$ and $\sqrt{0.029}$ km s^{-1}, i.e. 215 and 170 m s^{-1}, respectively, for the pics at 47.44 and 39.05 cycle d^{-1}. The phasing of the radial velocities to the derived periods confirms their reality (Fig. 2, bottom), as well as the corresponding radial velocity amplitudes (typically 200 m s^{-1}). The correction of an adjustment of the radial velocities with the superposition of two sinusoides with periods fixed to the above values leads to a decrease in the radial velocity dispersion from 252 to 182 m s^{-1}, which is still well above the uncertainties, 65 m s^{-1} on average. However, note that these uncertainty values suppose that the spectra are identical and only shifted from one to the other due to the Doppler-Fizeau Effect. They should be larger considering variations in the shape of the lines. This adjustment is reached for values of the amplitude of 216 and 149 m s^{-1}, respectively, for the periods corresponding to 47.44 and 39.05 cycle d^{-1}.

These results agree with those obtained by Koen et al. (2003) from dedicated photometry and spectroscopy. These authors indeed report detecting of at least 18 pulsation modes in β Pictoris, with a large number of spectra spread over 2 weeks, and detecting 2 low amplitude (≤1.5 mmag) pulsation modes in photometry, with frequencies equal to 47.44 cycle d^{-1} and 39.05 cycle d^{-1}, namely the same as we develop here. We are not able to detect other high frequencies, maybe because our temporal sampling is not really adapted to seeking high frequency variations.

The presence of pulsations in the case of β Pictoris is not really surprising, as this star belongs to the left side of the range of B-V, where the Instability Strip intersects with the Main Sequence (Eyer et al. 1997). As the frequencies of the variations are larger than 0.25 cycle d^{-1} (periods inferior to 6.5 h) and the stellar mass is larger than 1.9 $M_{\odot}$, β Pictoris probably belongs to the pulsating δ Scuti stars, which undergo non radial pulsations of p-mode excited by the κ mechanism with He II (Handler et al. 2002; Breger et al. 2000).

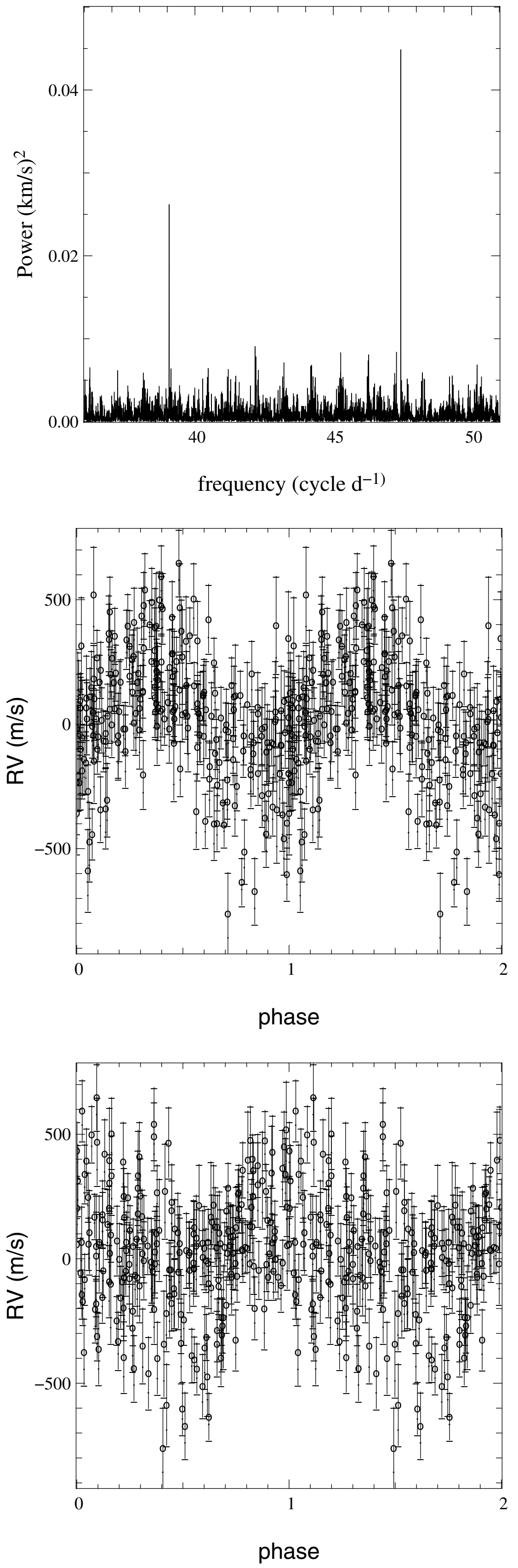

Fig. 2. High frequency periodograms of the radial velocities obtained on β Pictoris using the HARPS spectrograph (*top*) and the phasing of the radial velocities to the corresponding periods (*bottom*). The periodograms were obtained using the CLEAN algorithm (see text).

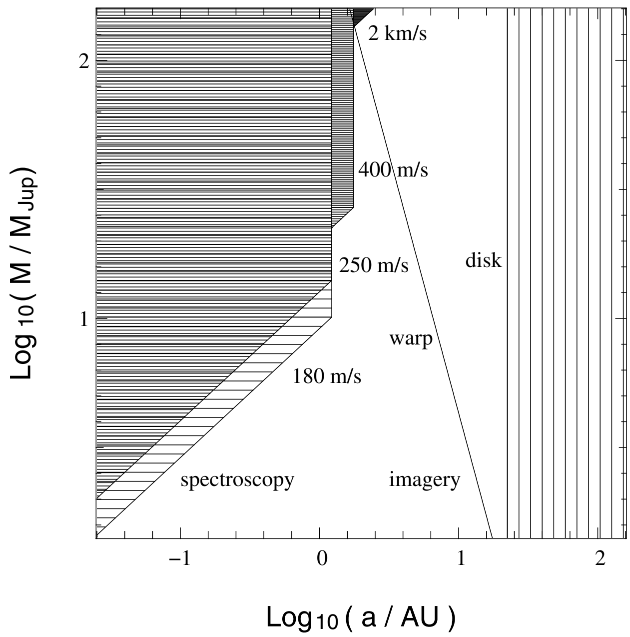

Fig. 3. Domain of [mass (M)/separation (a)] where the presence of a planet around β Pictoris is excluded by this radial velocity study (hashed zones, *left*): limit of 180 and 250 m s^{-1} correspond to HARPS, 400 m s^{-1} to CORALIE. The straight line indicates the possible characteristics of the planet responsible for the warped disk (Mouillet et al. 1997). The disk location is also indicated (*right*).

5. Exclusion domain for a planet around β Pictoris

The periodogram of the HARPS radial velocities, now corrected from the variations induced by the pulsations found above, does not show any clear peak in a period range of 1–180 days. Assuming a circular orbit again, we can still exclude the presence of a planet with a period lying typically between 1 and 350 days (hence a separation between 0.03 and 1.2 AU), but this time with an induced radial velocity semi-amplitude decreasing to $\approx$180 m s^{-1} (Fig. 3), which corresponds to the radial velocity dispersion after correction of the pulsations.

In Fig. 3, we reproduce the planet (mass, separation) domain constrained by the presence of the warp (Augereau et al. 2001; Mouillet et al. 1997), the present radial velocity measurements (limit of 180 and 250 m s^{-1} correspond to HARPS, 400 m s^{-1} to CORALIE), as well as older ones obtained by Lagrange et al. (1992; dispersion of 2 km s^{-1}, corresponding then to the achieved precision). The present analysis clearly constrains a new and important part of the domain.

6. Conclusions

In the frame of the search for extrasolar planets and brown dwarfs around early-type stars, we obtained a large number of spectra of β Pictoris over several months with the CORALIE and HARPS spectrographs. The radial velocities obtained exclude the presence of an inner giant planet in the β Pictoris system. Yet, these radial velocities are significantly variable, and we attribute at least a part of these variations to pulsations of δ Scuti type. Because of the effects of pulsations on the radial velocities, the stars belonging to the intersection of the Instability

Strip and the Main Sequence, such as β Pictoris, have to be carefully studied when looking for planets.

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