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ASTRONOMY AND ASTROPHYSICS

β Pictoris light variations

I. The planetary hypothesis

A. Lecavelier des Etangs[1,2]**, A. Vidal-Madjar**[1]**, G. Burki**[3]**, H.J.G.L.M. Lamers**[4]**, R. Ferlet**[1]**, C. Nitschelm**[1]**, and F. Sèvre**[1]

[1] Institut d'Astrophysique de Paris, CNRS, 98 bis boulevard Arago, F-75014 Paris, France
[2] NCRA, TATA Institute of Fundamental Research, Post Bag 3, Ganeshkhind, Pune University Campus, Pune 411 007, India
[3] Observatoire de Geneve, CH-1290 Sauverny, Switzerland
[4] Astronomical Institute and SRON Laboratory for Space Research, University of Utrecht, Utrecht, The Netherlands

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Abstract. The β Pic disk is probably a young planetary system in the clearing-out phase and similar to ours 4 billion years ago. The understanding of that system may shed light on the origin and evolution of our own planetary system. A very important question is related to the presence of large bodies, from kilometer size to planets. It is shown that many indirect arguments seem to indicate that even large planets must be already formed within the system.

Because it is seen nearly edge-on, photometric observations of the star were carried on in order to detect some signatures of inhomogeneities within the dust disk. This edge-on geometry is also very favorable to detect an eventual occultation by an object orbiting the star. An exceptional and significant photometric event was observed on Julian Day 2444918 (Nov 10, 1981), when the lightcurve shows a brightening during about 10 days with a central dip during less than one day. We discuss several possible explanations. The two most likely ones are: (1) occultation by a planet that is located in the dust disk, with a dust-free area around the planet, (2) the passage of a large cloud of dust with a highly forward peaked scattering in front of the star.

In this paper we model the predicted lightcurve for the occultation by a planet in a dust ring. The model takes into account the partial occultation phase and the limb-darkening effect. Even fine details of the light curve can be explained by this model. We find that the planet is of about Jupiter size and orbits the star at a distance of about 5 AU. We discuss the strong and the weak points of this model. The model of the forward scattering dust cloud is studied in a separate paper.

Key words: stars: circumstellar matter – planetary systems – stars: β Pic

Send offprint requests to: A. Lecavelier des Etangs

1. Introduction

Despite many observational advances over the past decades (see e.g., Schneider 1995), our Solar System remains the only well-studied planetary system around a main sequence star. It contains objects formed 4.5 billion years ago, from comets and asteroids to massive planets like Jupiter. Surprisingly, three planets have tentatively been detected around the millisecond pulsar PSR 1257+12 (Wolszczan 1994), a Jupiter-mass companion to the star 51 Pegasi at only 0.05 AU from the star is inferred from radial velocity measurements (Mayor & Queloz 1995), and planets has been discoved around other stars (e.g., Marcy & Butler 1996). These examples reveal the probable diversity of plausible planetary systems yet to be discovered as suggested by Lissauer (1995).

On the other hand, there is ample evidence that disks are common around young stars (see e.g., Beckwith & Sargent 1993). Theoretical studies suggest that planetary systems can form within the typical observed lifetime of these disks (Lissauer 1993) implying that possibly planetary systems around main sequence stars could be relatively common.

From a large body of observational approaches, an unique case of a main sequence star emerges: β Pictoris, surrounded by a disk of gas and dust (Aumann et al. 1984; Smith & Terrile 1984; Hobbs et al. 1985; Kondo & Bruhweiler 1985; Vidal-Madjar et al. 1986). This system may offer indirect clues to the presence of a large range of sizes of bodies orbiting the star.

Since 1984 a lot of work, both observational and theoretical, has been done to understand the β Pic system (Ferlet & Vidal-Madjar 1995). Although only the presence of micron-sized particles is largely accepted (see the review by Artymowicz 1995), there is also evidence for the existence of larger bodies from kilometer size to planetary sizes. We will review in Sect. 2 the chain of independent arguments which seem to suggest very strongly that massive bodies are already formed around β Pic. In Sect. 3 we will present and discuss the photometric observations completed in 1981, before β Pic was identified as a possible young planetary system. In Sect. 4 and 5 we will discuss the different plausible scenarios that might explain the photometric variations, both the unlikely ones (Sect. 4) and the likely ones (Sect. 5). Of the two likely explanations, we discuss in this paper the model of occultation by a planet located within an empty sphere of influence, that is located in the dust disk of β Pic. The alternative model of a large forward-scattering cloud is discussed in a separate paper (Lamers et al. 1997).

2. Evidence of large bodies around β Pic

β Pic is a very good candidate to search for planets. Indeed, its gas and dust disk presents a large number of characteristics of a young planetary system seen edge-on from the Earth. Here we present a list of arguments for the presence of large bodies.

2.1. Comets seen through their ejecta

The thermal emission from the central part of the β Pic disk shows a silicate emission feature at 10μ (Telesco & Knacke 1991). This feature is different from all known emissions except that it is remarkably similar to those observed in comets which have emissions characteristic of crystalline silicates (Knacke et al. 1993). This seems to indicate that possibly some cometary-like objects are already present within the β Pic system.

Independently, the stable component of the gaseous disk has also been subject to intense investigations (Ferlet & Vidal-Madjar 1995). Among many results, we point out the detection of CO absorption by HST-GHRS (Vidal-Madjar et al. 1994) which gives evidence to the presence of evaporating bodies. The CO molecule is destroyed very rapidly by the ambient interstellar UV light at frequencies $\nu \sim 1.4 \cdot 10^{-10}\mathrm{s}^{-1}$, and thus the CO gas must be supplied by a permanent internal source. An obvious possibility is continuous quiescent evaporation of comets at several tens of AU from the star.

The presence of a dust disk is also very challenging: the time scale of dust destruction is much smaller than the age of the star (Weissman 1984, Backman & Paresce 1993). This means that the disk must be continuously replenished either by collisions between larger bodies or, more probably, by evaporating bodies. Indeed, Lecavelier des Etangs et al. (1996a) have shown that a disk which is continuously supplied by orbiting (slowly) evaporating bodies (OEB) perturbed by a planetary system, can have the same spatial distribution of dust as the distribution observed around β Pic. This new model may be able to explain the main characteristics of the disk, such as the power law of the radial dust distribution and asymmetries observed at large distances. It is compatible with the CO detection and requires the presence within the disk of orbiting and evaporating large bodies at tens of AU from the star.

2.2. Comets seen individually: falling evaporating bodies

Spectroscopy revealed strongly variable absorption lines in the visible (Ferlet et al. 1987, Lagrange et al. 1987) and the UV (Vidal-Madjar 1994 et al., and refs. therein). These very sporadic and mostly redshifted absorption lines are now very well explained as due to matter falling onto the star (at velocities up to 400 km s^{-1}). Complete dynamical simulations have reproduced the observed redshifted events as due to evaporating comets, of sizes more than a kilometer, falling towards β Pic. (Beust et al. 1991a). This Falling-Evaporating-Bodies (FEB) scenario has predicted unusual line ratios which have indeed been observed (Vidal-Madjar et al. 1994). Finally, hydrodynamical calculations of the flow of metallic ions around their evaporating parent bodies give a possible explanation for the very presence of AlIII and CIV lines (Deleuil et al. 1993). The ions can be produced through collisions within the coma, because the stellar radiation of an A5V star is unable to create these highly ionized species through photoionization (Beust & Tagger 1993). All these different aspects of the observed spectral variations can hardly be explained by any other model, and none was ever proposed. So there is strong evidence that at least kilometer size bodies are already present within the β Pic system.

2.3. Massive bodies needed

The exact mechanism that could generate these numerous star-grazers (Ferlet et al. 1993) is still controversial, but planetary perturbations are thought to be the basic process. Several explanations have been proposed. The hypothesis of an unique family of fragments from a single large body like comet D/Shoemaker-Levy 9's fragments, (i.e. SL9's fragment falling into Jupiter) cannot explain all the observational constraints (Beust et al. 1996). Therefore, one needs to assume that many bodies must be gravitationally perturbed by one or several planets.

A single perturbation by a single planet requires a massive planet with a large eccentricity ($e \geq 0.6$). Although it could *a priori* seem unrealistic, a massive planet with an eccentricity of 0.6 has recently been discovered in orbit about 16 Cyg B by Cochran et al. (1996). Alternatively, long term perturbations by massive planets have been suggested through two different mechanisms: secular resonances or mean motion resonances. A secular resonance occurs when the precession frequency of the longitude of periastron or alternatively of the longitude of the ascending node of the perturbed body is commensurate with one of the frequencies of the planetary system. A mean motion resonance occurs simply when the mean motion is commensurate with the mean motion of a planet. Both could provide the observed asymmetry in the longitude of periastron of the FEBs ($\omega \sim 30^o$, see discussion in Beust et al. 1996). On one hand, secular resonances can be very efficient, such as the so-called ν_6 resonance with Saturn in our solar system (Levison 1994), but unfortunately a general theory is still needed. On the other hand, Beust & Morbidelli (1996) have shown that mean motion resonances can generate star-grazers with all the observed characteristics of the FEBs.

The distribution of dust around β Pic also might give indirect evidence for the existence of planets. The dust distribution is very asymmetric close to the star and the central part of the disk is relatively free of dust (Lagage & Pantin 1994). These dust distributions and inhomogeneities could be explained by planetary perturbation (Scholl et al. 1993, Roques et al. 1994). However, an explanation for the observed asymmetries of a factor larger than 3 between the infrared emission of the two extensions of the disk is still needed (Lecavelier des Etangs et al. 1996b).

In conclusion, there are many indirect indications that a planetary system is already formed around β Pic with a multitude of bodies with a large range of sizes. The large number of comet-like bodies (FEBs) even suggests the presence of massive planets. However, up to now there is no direct evidence for the existence of planets around β Pic.

3. Photometric variations

Here we present the analysis of the photometric variations which could be connected with the transit of either a giant planet or a scattering dust cloud in front of the star.

In order to study the inhomogeneities in the edge-on disk of β Pic, we decided to look for the stellar light variations to scan the dust disk structure through its variable extinction. We analysed photometric measurements of the Geneva-photometry from Nov 18, 1975 to Feb 27, 1992 (JD 2734 to JD 8679, where JD is for Julian Day - 244000) (Rufener 1989). Since 1975, β Pic had been used as a photometric reference star. In 1982 it was noted that β Pic was showing some unexplained variations and thus was eliminated from the list of the Geneva Observatory reference stars in 1982. At that time the "Vega-like" phenomenon of β Pic was not yet known. Unfortunately, the consequence was that this star was not photometrically observed any more until 1988, when we suggested to start again its survey, because by then the star was known to have a disk seen edge-on.

3.1. Long time scale variations

The data are composed of 238 magnitude measurements between 1975 and 1992, in seven bands: three wide U, B and V bands, and four narrower B_1, B_2, V_1 and G bands. They are associated with a quality factor from 0 to 4, from lowest to highest accuracy. The detailed analysis of the photometric variations can be found elsewhere (Lecavelier des Etangs et al. 1995). Here we present a summary of these variations and new possible interpretations.

The main result of the analysis of the long time scale variations is that β Pic shows an achromatic linear brightness increase from Feb 21, 1979 to Feb 17, 1982, with a slope $dm/dt = -1.1 \cdot 10^{-5} \pm 0.4 \cdot 10^{-5}$ mag. per day in all seven bands (Fig. 1). In contrast eight other stars used as references did not show any variation at all.

We cannot completely exclude the presence of intrinsic stellar variations, although such achromatic stellar variations would be surprising. On the other hand, these variations could be compatible with disk inhomogeneities of 10% to 20% in the azimuthal distribution of the dust in the disk. Indeed, it has been demonstrated that the presence of a planet in the disk can produce inhomogeneities, such as arcs or accumulation of matter following planet trajectories (Scholl et al. 1993, Roques et al.

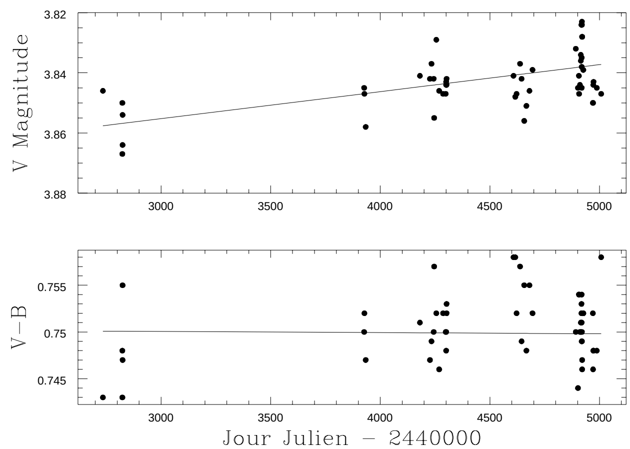

Fig. 1. Photometric measurements of β Pic from 1975 to 1982. The linear fit gives evidence that the long term variations are significant. The plot of the V-B index shows that the variations are achromatic.

1994). These structures could explain the variations on a long time scale. However, due to the collisional destruction of dust particles, these structures can be supplied by mean motion resonances only if the vertical optical depth is not larger than a critical one: $\tau_{crit} \sim 4 \cdot 10^{-4}$ (Artymowicz 1995, Lecavelier des Etangs 1996b). The consistency of a small dust vertical optical depth and variations of about 0.01 magnitude is questionable. The disk thickness would have to be smaller than 1 AU at 20 AU from the star, which corresponds to an opening angle smaller than 2 degrees. These quantities are different from the large disk thickness and opening angle measured on the disk image at larger distances. But the observation does not constrain the vertical structure of the inner disk. The apparent paradox could thus be solved if some extinction is due to a flat ring of larger particles (up to few centimeters) similar to the planetary rings in the Solar System which cannot be detected by infrared observations.

3.2. Short term variations

Among the stars we have analysed in the Geneva photometry, only two have shown short term variations each on one occasion with a confidence level of 99%: HR 10 with a strong color dependency and β Pic during November 1981 with little or no color dependency. For β Pic, the probability that these variations are produced by only statistical noise is less than 10^{-5} (Lecavelier des Etangs et al. 1995). We emphasize that short term variation of that type is an unique case observed in all Geneva Observatory data. The photometric observations around this period and the mean magnitudes outside this short interval are listed in Table 1.

The variation of β Pic in November 1981 can be separated into two parts (Fig. 2). The brightness of β Pic slowly increased by about 0.06 magnitude in about 10 days, and symmetrically slowly returned to normal. But at the center of this variation, near the maximum increase, on JD 4918 (= Nov 10, 1981), there was a sharp decrease.

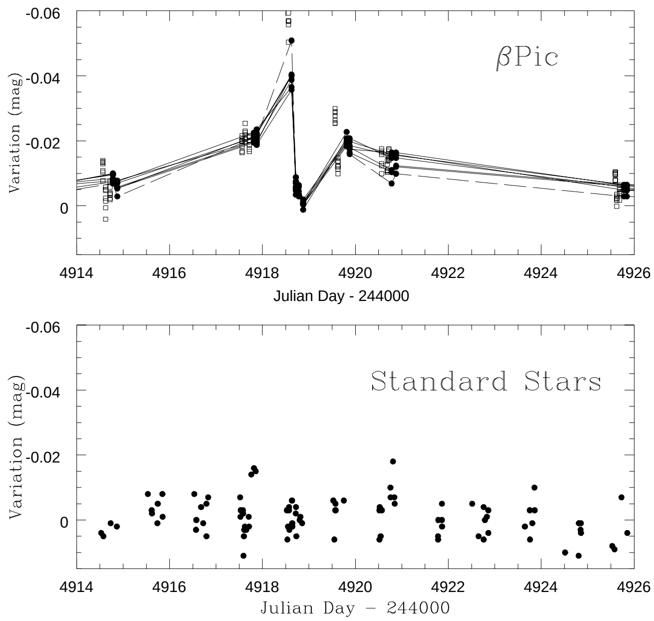

Fig. 2. The short term magnitude variations of β Pic in the seven bands around JD 4918. The dashed line represents the variation in U band. Good quality measurements (quality factor greater than 2) are connected and represented by dots, the others ones are represented by open squares. These variations have no color dependency (except for the point when the brightness increase was at its maximum: there the increase could be larger in U.) Note the slow increase and decrease in brightness with a dip in the middle. The bottom panel gives for the same period the difference between the individual values and the mean magnitude for all the standard stars. The measurements of these stars are normal with a relative dispersion of the measurements due to statistical noise of only $\sigma \sim 5 \cdot 10^{-3}$ mag.

The first measurement of this particular night gives the brightest measurement of β Pic: the star was about 0.06 magnitude brighter than the mean magnitude in all seven bands except for the U band, for which the variation rises 0.09 magnitude above average level. Unfortunately the quality of these measurements obtained with an air mass of 2.4 is not guaranteed at the same level of confidence and thus they must be considered with care. However a plot of the observations of eight other stars used as references clearly shows that no systematic errors are present and that the air mass correction even at the 2.4 level is accurate (Fig. 3). This measurement on JD 4918.563 is thus significant although the accuracy is probably smaller than for the following measurements. 1.5 hours later the star was 0.04 magnitude brighter than the mean magnitude, except in the U band where the variation was 0.05 magnitude. The three last measurements were obtained between 4 and 7 hours later. At that time β Pic was close to its normal brightness but still decreasing (Fig. 4). Given that the variance of the data in a single day is about σ^2 = 1.5 $\cdot$ 10^{-5} (a value smaller than the dispersion related to all the data in which there are systematic errors from day to day), a χ^2 test gives a confidence level of 83 % to consider that this slope is real and not due to statistical fluctuations. We will see in Sect. 6 that this slope could be related to the limb-darkening of the stellar photosphere.

Table 1. Magnitude and colors measurements on β Pic between JD 4914 and JD 4926 with quality factor greater than 2.

Date (JD)	V	U-B	V-B	B1-B	B2-B	V1-B	G-B
4914.780	3.834	1.492	0.751	0.948	1.440	1.459	1.908
4914.857	3.836	1.493	0.750	0.947	1.440	1.458	1.907
4917.804	3.824	1.489	0.752	0.945	1.440	1.457	1.907
4917.857	3.824	1.490	0.753	0.945	1.441	1.457	1.909
4918.628	3.805	1.478	0.752	0.945	1.438	1.462	1.910
4918.720	3.835	1.490	0.749	0.947	1.442	1.458	1.908
4918.786	3.838	1.492	0.751	0.945	1.438	1.460	1.908
4918.856	3.845	1.490	0.754	0.947	1.439	1.460	1.907
4919.802	3.823	1.490	0.750	0.947	1.439	1.459	1.903
4919.853	3.824	1.491	0.749	0.947	1.439	1.458	1.903
4920.787	3.828	1.493	0.746	0.946	1.433	1.454	1.902
4920.859	3.828	1.491	0.747	0.945	1.434	1.455	1.903
4925.791	3.839	1.492	0.752	0.945	1.438	1.458	1.906
4925.847	3.839	1.492	0.752	0.945	1.439	1.458	1.907
Mean	3.844	1.488	0.751	0.945	1.438	1.459	1.906

It is interesting that the variations of β Pic around JD 4918 are approximately symmetrical around the dip in the light curve (see Fig. 2). We stress the fact that the atmospheric conditions were very good during this particular night, and for all of the other stars observed during that night the measurements were all totally normal. The measurements of the standard stars during this period are also plotted for comparison in Fig. 2.

4. Unlikely explanations

4.1. A bright spot on the star

The apparent similarity of the mean magnitude level of the star and the minimum level on JD 4918 is very interesting. This could be explained very naturally by a bright phenomenon which disappears behind the star during the JD 4918 measurements.

A bright spot on the rotating star would have been able to produce such an effect. However β Pic is an A5V star with probably no convective zone reaching its surface and thus probably with no photospheric bright spot. In any case, with $v \sin i$ = 130 km s^{-1} and a rotation period of 16 hrs, a spot on the star is visible during less than 8 hours, and measurements on JD 4917 and 4919 are spread over more than 7 hours. During this time, the putative bright spot should have strongly changed the magnitude measurements, which did not occur.

The interactions between a shower of FEBs and the stellar photosphere might have produced a temporary brightening. However, again in this case one might expect to see some rotational modulation, which is not observed. We conclude that the photometric variations of β Pic are probably not due to a bright spot on the stellar surface.

4.2. A cloud of backward scattering dust

In the same manner, we could expect that a cloud of backward scattering dust moving behind the star could be responsible for

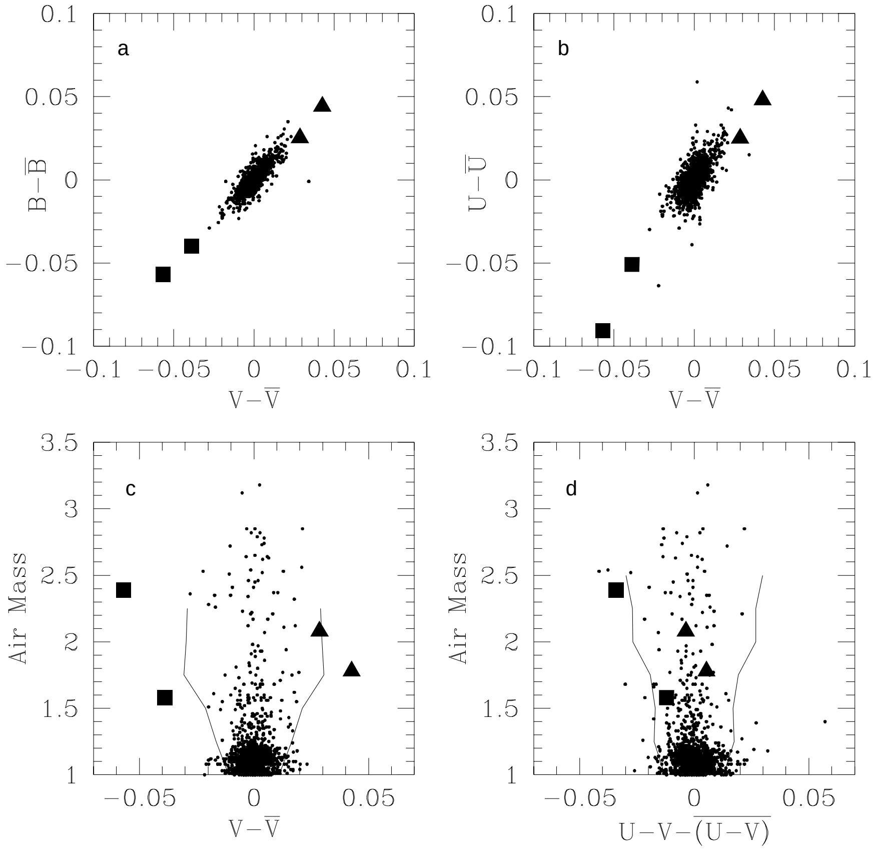

Fig. 3a–d. Plot of magnitudes, color variations and air mass for 9 stars observed from 1970 until 1992. Squares are for the two first measurements for β Pic on JD 4918. Triangles are for the two extreme measurements of the star HR10, which also showed photometric variability and spectroscopic similarities with β Pic. **a** B variations versus V variations. The statistical variations around the mean magnitude in B band are strongly correlated to variations on V band. The measurements of β Pic are within the diagonal correlation, which implies that there is no color variation in B-V. **b** U variations versus V variations. There is again a correlation between V and U bands. β Pic shows a color variation, but it is within the uncertainty of the U-band measurements. **c** V variations versus air mass. The solid lines represent the standard deviation 2σ as a function of the air mass. This plot shows that air mass corrections are accurate up to large zenithal distances. The variations of β Pic (and HR10) are obviously outside the 2σ statistical noise and are clearly not due to the atmospheric extinction. **d** U-V variations versus air mass. The variations of β Pic in U-V are at about the 2σ noise level.

the observed variations. The increased emission can suddenly be hidden behind the star, to explain the coincidence of the mean magnitude level and the minimum observed on JD 4918.

The variation of the star brightness (F) due to a back scattering cloud can be described as follows:

$$\frac{\Delta F}{F} \approx \frac{R_{\mathrm{d}}^2 \cdot Q_{\mathrm{sca}} \cdot P(\theta)}{d^2}$$

with $\Delta F/F \approx 0.04$, where $P(\theta)$ is the scattering phase function normalized by $\int P(\theta) d\Omega = 1$, Q_{sca} is the scattering efficiency and R_{d} is effective scattering radius of the dust cloud at a distance d from the star. With $Q_{\mathrm{sca}} \approx 2$ and $P(\theta = \pi) \leq 0.02$ for the zodiacal dust or a planetary ring (Hong 1985) we must have $R_{\mathrm{d}}/d \approx 1$. This would require a very large dust-cloud with a radius approximately equal to its distance from the star. Such a large cloud is inconsistent with the short duration of the dip in the lightcurve and could not be totally hidden if it is larger than the star.

4.3. Gravitational lensing

As already suggested by Lecavelier des Etangs et al. (1995), the abrupt drop in β Pic could be due to a planet passing in front of the star. If this is true, we need to find an explanation for the brightness increase before and after the occultation due to the environment of the putative planet.

In this case, the well known microlensing effect (e.g., Paczyński 1986) is in fact not efficient. The Einstein radius of a planet around β Pic is

$$R_E = \sqrt{\frac{4GM_p d}{c^2}} \approx 2000 \sqrt{\frac{M_p}{M_J} \frac{d}{5AU}} \text{ km}$$

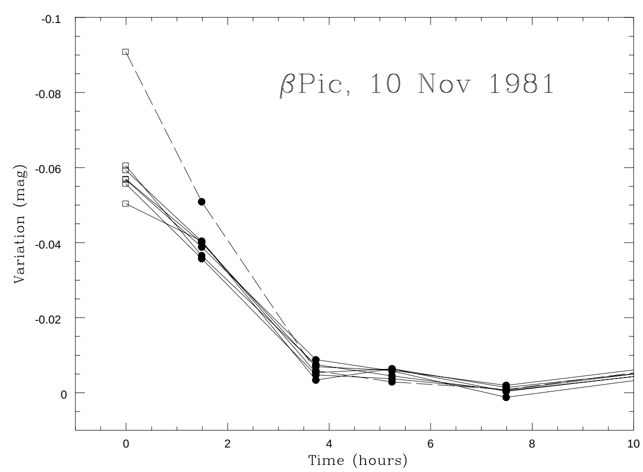

Fig. 4. Plot of β Pic magnitude variations on JD 4918. The time is given in hours relative to the time of the first measurements of this particular day. The dashed line represents the variation in U band. The first measurements have been obtained through an air mass of 2.4 and are represented by open squares. The other data have very good accuracy (quality factor equal to 3)

where M_p and M_J are the mass of the putative planet and Jupiter respectively, d its distance to β Pic. This radius is smaller than the planet size, so gravitational lensing can not account for the observed brightness increase.

4.4. Refraction by the atmosphere of a planet

The expected brightness increase due to refraction by the atmosphere of a planet is:

$$\Delta F/F \approx \frac{H}{\omega\, d}$$

where H is the scale height of the atmosphere ($H \sim 10$ km) and ω is the refraction angle. We assume a distance of $d \sim 10^9$ km and a planet radius of $R_p \sim 10^5$ km. Just before the planet occultation the diffraction angle is $\omega \sim R_p/d \sim 10^{-4}$. So diffraction by the atmosphere of the planet would produce a brightness increase of $\Delta F/F \approx 10^{-4}$. This effect is too faint to explain the observed brightness increase.

Note however, that if the planet is surrounded by a large disk or torus of gas with a scale-height of $H \sim 0.1\ R_p$, this explanation of the brightness increase might be acceptable.

5. Explanations which could work

5.1. A cloud of forward scattering dust

Although a backward scattering dust cloud cannot explain the observed brightness variations of β Pic (sect. 4.2), forward scattering can be much more efficient. If the dust particles produce optical refraction, the phase function in the forward direction might reach very high values of $P(0) \sim 100$. Thus, the forward scattering by a dust cloud of few stellar radii in size located at about one AU can cause detectable light variations when it passes in front of the star. Combined with occultation by the optical thick part of the cloud, such a model might explain both the brightening of β Pic and the dip in the lightcurve. This model will be investigated in a separate paper (Lamers et al. 1997, Paper II).

5.2. A hole in the dust disk due to a planet

The observed photometric variations of β Pic are compatible with the transit of a planet in front of the star (Lecavelier des Etangs et al. 1995), if the sphere of influence of this putative planet is free of dust.

We propose that the enhancement of brightness of β Pic around JD 4918 may be due to the passage of this cleared out zone in front of β Pic. The cleared region will have a radius of the "Hill-radius", which is the distance from the planet at which the planet's gravity equals the tidal force of the star's gravity. With the stellar mass given by Lanz et al. (1995): $M_{\beta Pic} = 1.8 M_\odot$, we have

$$R_H = \left(\frac{M_p}{3M_{\beta Pic}}\right)^{1/3} d = 0.28 \left(\frac{M_p}{M_J}\right)^{1/3} \left(\frac{d}{5\mathrm{AU}}\right) \mathrm{AU} \qquad (1)$$

where M_p is the mass of the planet. To cover a distance equal to its Hill radius, the planet needs a time t_H:

$$t_H = 27 \left(\frac{M_p}{M_J}\right)^{1/3} \left(\frac{d}{5\mathrm{AU}}\right)^{3/2} \text{ days}$$

Note that this time is of the order of the duration of the brightening observed around JD 4918, within the uncertainty of such simple approximation. So the brightening of β Pic could be due to the passage of a cleared zone in the dust disk around the star, if the system is seen edge-on.

The central dip in the lightcurve could be due to occultation by the planet itself. An occultation by the supposed planet crossing a diameter of β Pic will last a time $t_\star \leq 1.1(d/5\mathrm{AU})^{1/2}$ days, again in reasonable agreement with the observed duration of the dip in the light curve. Occultation will decrease the brightness of the star by $\delta V \sim 10^{-2}(R_p/R_J)^2$ (where R_p and R_J are the radius of the planet and Jupiter). Thus, the measurements of JD 4918 could be explained by an occultation of the star by a planet whose radius is slightly larger than that of Jupiter (Lecavelier des Etangs et al. 1995). Below we describe a detailed model.

6. A model for the occultation by a planet

In this section we develop the two phases of this phenomenon. We shall analyse the sphere of influence, and finally we will conclude on the parameters which can be derived from a model of planetary occultation.

6.1. A dust-free sphere of influence

The explanation of the brightening of β Pic by the passage of a cleared out zone in the dust ring in front of the star requires two properties. (a) The Hill sphere must be cleared of dust. This is necessary to reduce the extinction before and after the occultation. (b) The dust disk must be seen edge-on and produce an extinction larger than 0.06 mag. within a radial extent about equal to the radius of the cleared region around the planet. This is necessary to explain the amplitude of the variation.

To show the effect of the Hill sphere, we carried out the dynamical evolution of particles in resonance 1:1, i.e. with the same orbital period as the planet. Numerical simulations have been done with a model developed on the CM5 massively parallel computer. The program calculates the spatial distribution of dust at the equilibrium between injection by large bodies and destruction by collision (Lecavelier des Etangs et al. 1996b). The particles are assumed to be produced by parent bodies in a similar manner as described by Lecavelier des Etangs et al. (1996a), i.e. following the relation between the eccentricity of the orbits of dust grains and the β ratio of radiation forces to gravitational forces: $e_\beta = \beta/(1-\beta)$.

The initial and final stage of such a model are represented in Fig. 5. We see that particles in 1:1 resonance are trapped around the L_4 and L_5 Lagrangian points. The Poynting-Robertson (PR) effect perturbs the orbits of dust particles around the star, so

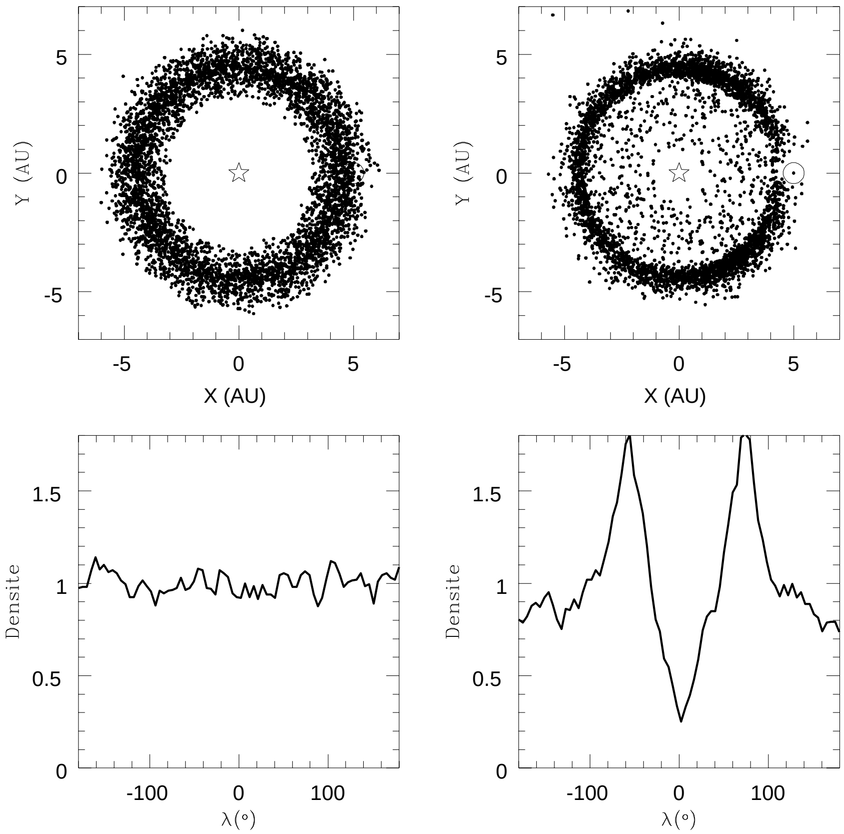

Fig. 5. Spatial distribution of dust in resonance 1:1 with the planet. The initial conditions are given at the left, with the azimuthal distribution at bottom. The steady state is given at the right. The influence sphere is represented by a circle around the planet. We see that at the steady state this region is free of dust, and that there is accumulation of matter around the two L_4 and L_5 Lagrangian points. These over-densities are located at $\pm 60^o$ from the planet.

that they evolve into horseshoe orbits which continuously expand in size, until they reach close encounters with the planet (see also Liou & Zook 1995a and 1995b). Then these particles are accreted or ejected into very eccentric orbits. Therefore, at the steady state between particle injection and destruction, the influence sphere of the planet is clear of dust. Moreover, the regions around the Lagrangian points have large over-densities. We can thus explain not only the brightness increase during few days before and after JD 4918 by the cleared influence sphere, but also the brightness increase on long time scale which were observed before, i.e. the decrease of about 0.01 magnitude from 1979 to 1982. This variation can be interpreted by the slow decrease of the extinction by matter gathered around one of the Lagrange points: this region of over-density is rotating at the same speed as the planet.

At a first glance, it seems that the three different variations are simultaneously explained: the slow brightening from 1979 to 1982 by the over-densities of the dust ring in a Lagrangian point, the variations before and after JD 4918 by the hole around the influence sphere of the planet and the dip in the lightcurve on JD 4918 by the planet occultation. However, the second requirement is a strong hypothesis: the extinction by dust or bodies in 1:1 resonance must be relatively large. This can be consistent with the infrared observations if the dust ring is flat and has an opening angle smaller than the outer part of the disk. In that case, the extinction can be relatively large in a small solid angle covered by this ring, and the total absorption can be small and consistent with the total infrared emission. Indeed, there is no reason to believe that the inner part of the disk at few astronomical units has an opening angle as large as the opening angle of the outer part, simply because the opening angle of the outer disk is due to the inclination distribution of the dust parent bodies (Lecavelier des Etangs et al. 1996a). Alternatively, as suggested in Sect. 3.1, there could be a flat ring of large particles in which dissipative collisions play the same role as the Poynting-Robertson drag. In conclusion, all the observed variations can be explained if a flat ring of particles is orbiting with a planet, except for its sphere of influence which would be relatively clear of dust.

6.2. Constraints from the occultation light curve

The dip in the lightcurve on JD 4918 might be due to occultation by the planet, independent of the explanation of the brightening. We compare the observations with detailed calculations. During the phase when the projected planet disk partially occults the stellar disk, the star light must quickly decrease (hundredths of magnitude per hour). The observed duration of this partial occultation phase is of the order of hours. Moreover, during the occultation, the planet hides different regions of the stellar surface along its path from limb to limb, depending on the impact parameter. Thus, due to the stellar limb-darkening, the light curve must present a very well defined shape.

We carried out calculations of a planet occultation taking into account the limb-darkening and the partial occultation

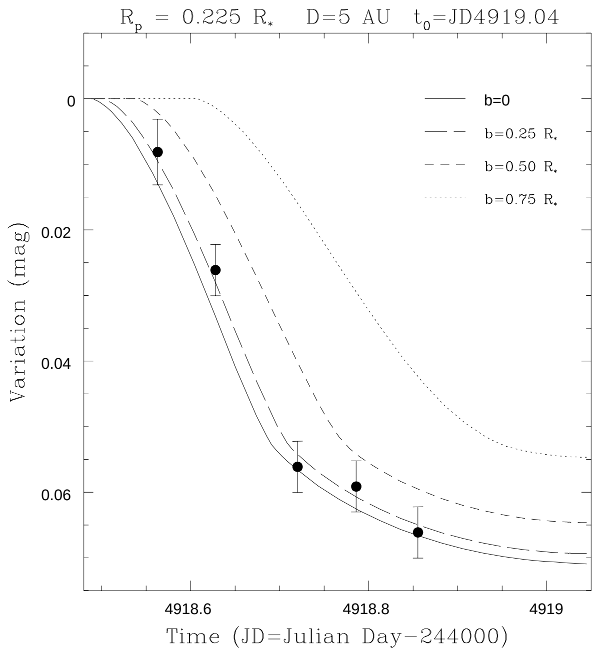

Fig. 6. Variations of a star brightness due to an occultation by a planet as a function of the time assuming a planet distance of 5 AU. b is the impact parameter in stellar radius (R_*). The planet radius is R_p = $0.225R_*$. The limb-darkening and partial occultation are taken into account. The β Pic magnitude measurements has been plotted assuming a differential brightness of 0.064 mag between the mean magnitude of β Pic and the magnitude just before the occultation.

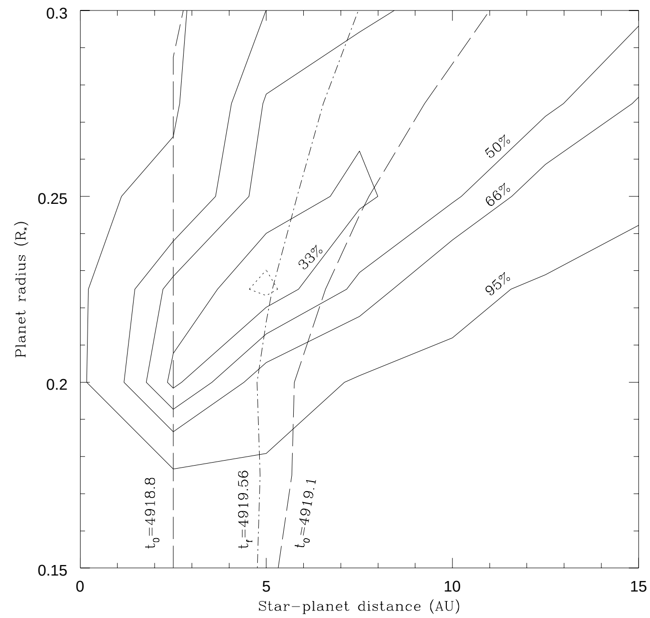

Fig. 7. Plot of the isoprobability of χ^2_3 of the squared differences between the data and the model as a function of given R_p and d. The dotted contour gives the best fit with R_p=0.225 and d=5 AU. The solid line contours represent the domain compatible with the data at a level of respectively 33%, 50%, 66% and 95%. Thus the planet radius must be greater than 0.2 stellar radius. A strong correlation is found between the possible distance to the star and planet radius. Dashed lines represent places where the time of central occultation, t_0, must be JD 4918.8 and JD 4919.1. If the variations before and after JD 4918 are actually symmetrical, then we must have t_0 = 4918.95 $\pm$ 0.15 (Lamers et al. 1997), and the region outside the zone given by these two limits must not be considered. Dot-short dashed line represents places where the final time of occultation t_f must be JD 4919.56 which is the date when the first measurements of the next day was obtained. If at that time the occultation is already finished, then the zone at the right of this line is not compatible with the data. Thus, the distance between the star and the putative planet must be less than 8 AU.

phase. The input parameters of such a model are R_p and b, respectively the radius of the planet and the impact parameter (both in unit of stellar radius), d the distance to the star, m_0 the magnitude of the star through the disk just before and after the occultation, and t_0 the time of central occultation.

There are five parameters and we have only five measurements! However if the data would not present a sharp decrease followed by a longer slow one, they would never be compatible with such a model. Indeed, due to the limb-darkening of the stellar photosphere, any solution *must* present a slow decrease after the sharp one produced when the planet starts to pass in front of the star. This is exactly the behavior of the observed light variations.

Moreover, the five measurements of JD 4918 are only compatible with the set of solutions given by reasonable values of these parameters. The best fit is found for R_p=0.225, b = 0.2, d=5 AU, t_0=JD 4919.04 and $m_0 - \bar{m}$=-0.064 (Fig. 6).

For a set of values for R_p and d, we have computed the squared difference between the measurements and the best fits, the three other parameters being relaxed. We have plotted the χ^2_3 isoprobabilities of such a model with 3 degrees of freedom (Fig. 7). It can be seen that R_p must be greater than 0.2 stellar radius, which is derived from the relation between the planet size and magnitude variation. This size is much larger than the maximal possible size of cold gaseous planets whose radius can never be larger than 1.5 times the radius of Jupiter or 0.1 R_* (Saumon et al. 1996). There are however three solutions to that problem: either the planet is not gaseous, which is not expected, or it is a hydrogen dominated warm (young) gaseous planet with large radius in a youthful system, finally this putative planet can be surrounded by large rings which can contribute to the amplitude and duration of the photometric variation.

More importantly, d must be less than 8 AU in order to explain the short duration of the event and the fast variation on JD 4918. An eccentric orbit (not considered here) could slightly change this constrain. This gives a maximum period of 19 years, and the best fit with d=5 AU gives a most probable period of 9 years. A continuous survey of β Pic photometric variations is thus recommended.

6.3. U band variations

As it can be seen in Fig. 2, the variations do not show color signatures except for the two first measurements of JD 4198 when the brightness of β Pic was at its maximum and the U brightness increase was possibly 25% to 50% greater than for the other bands. If real (and not produced by atmospheric extinction), this phenomenon could be explained in the context of the occultation model. The extinction by dust in shorter wavelengths is expected to be larger than in longer wavelengths. Thus, a decrease of extinction must produce a larger increase of brightness in U band, and could explain the non-linearity in the color variation. However, as the planet occultation is achromatic, then the planet must be surrounded by material presenting the same larger extinction in the U band (dust rings?).

7. Discussion and conclusions

We discussed the evidence for the presence of large bodies km-size or larger, around β Pic. Falling evaporating bodies have been observed directly in the form of transient absorption features in spectral lines. The presence of orbiting evaporating bodies has been derived from the fact that the gaseous disk, e.g., observed in CO lines, and the dust disk have a destruction rate which is short compared to the age of the star. This requires a continuous replenishment of the gas and dust, e.g., by orbiting evaporating bodies. More massive planets are generally thought to be present but their presence is inferred only indirectly. The main argument is the perturbation of the orbits of smaller bodies, to explain the large number of evaporating bodies. The asymmetry of the dust disk close to the star might also be due to the presence of a planet.

An exceptional photometric event was recorded on JD 4918 (= Nov 10, 1981). The lightcurve shows an achromatic brightening by about 0.06 mag. in about ten days, and a slow decrease to the normal magnitude on about the same timescale. At maximum brightness, the lightcurve shows a short dip with a duration of less than a day. In Sect. 3 we discussed several possible explanations which in principle might explain the lightcurve but turn out to be not acceptable. The two explanations which can explain the general features of the lightcurve as well as the magnitude of the effect are: occultation by a planet surrounded by a dust-free zone, and an orbiting dust cloud with dust that has a strongly forward peaked phase function. In this paper we discussed the first model.

Because we know that the disk is seen almost edge on, with a tilt angle less than about 3 degrees (Kalas & Jewitt 1995) the probability of occultation is not negligible. We have modeled the lightcurve with a model consisting of a dust-ring around β Pic at the distance of the planet. The interaction with the planet has cleared the dust in a zone around the star. Part of this dust is now concentrated near the two Lagrangian points at 60 degrees angle from the line star-planet. The dust-ring is assumed to have an extinction of at least 0.06 mag. The clearing zone has about the same width as the dust ring and orbits the star with the same period as the planet. When the clearing zone enters the line of sight to the star, the extinction of the star decreases and the star gets brighter. When the planet, in the middle of the clearing zone, passes in front of the star its occultation produces the dip in the light curve. The detailed modeling indicates a most probable distance of the planet of 5 AU, and a radius 0.22 R_*, which is twice the size of Jupiter. This is larger than the size of gaseous planets. So either the planet is not gaseous (which is unlikely) or the planet is surrounded by a large ring that also contributes to the occultation. The calculated azimuthal distribution of the dust in the ring around the star with the concentration at the Lagrangian points, might explain the slow brightening of the star from 1979 to 1982.

This model is attractive because it can explain the three phases of the brightness variations of β Pic : the slow brightening, the 20-day brightening in November 1981 and the dip in the lightcurve on Nov. 19 1981. However it requires a few characteristics that are uncertain: (1) the inner dust disk around β Pic must be flat and have an extinction of about 0.06 mag. in the visual within a radial extent of the order of the diameter of the clearing zone, which is about 1 AU; (2) the orbit of the planet must pass exactly in front of the star. For a distance of 5 AU, and the upper limit for the tilt angle of the disk around β Pic of 3 degrees, this planet occultation has a probability of 2%.

In a separate paper we investigate the alternative explanation for the brightness variations of β Pic in terms of an orbiting forward scattering cloud (Lamers et al. 1997, Paper II).

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