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β Pictoris: its evolutionary status

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ABSTRACT

Since the discovery of a large infrared excess in β Pic, this star has been intensively studied, and is currently considered as one of the best candidates for being the centre of an extrasolar planetary system. Such a star will be surrounded by an asymmetric, edge-on dust disc extending beyond 10^3 au from the star. The suspected existence of a planetary system around β Pic has recently been strongly reinforced by the discovery of a central cleared zone about 40 au from the star. A disc warp has also been detected, the most straightforward explanation of which is the presence of at least a giant planet orbiting β Pic. Further evidence comes from the low gas-to-dust ratio, which may be due to the planetary system formation process.

Redshifted and highly variable circumstellar absorption lines of several ions have been interpreted as resulting from the evaporation of comets falling on to β Pic. Recently, the very existence of the dust disc was employed to attribute a small age to β Pic. However, the amount of dust produced by the evaporating comets has been shown to be sufficient to replenish the disc, making the arguments in favour of small ages no longer meaningful.

In the frame of the cometary hypothesis, we show that the analysis of the rate of events that would have been observed in the Solar system at different evolutionary stages argues in favour of a large age for β Pic. However, the estimation of stellar ages employing cometary fluxes should be treated with caution, on account of the diversity of possible planetary systems.

We also present a new analysis of the evolutionary status of β Pic in the framework of stellar evolution, showing that, with the present uncertainties, there is a continuum of possible ages for this star. However, employing the data deduced from the cometary flux, we obtain a consistent scenario of a large stellar age.

Key words: circumstellar matter – stars: evolution – stars: individual: β Pic – planetary systems.

1 INTRODUCTION

The bright nearby star β Pic is surrounded by a nearly edge-on, extended dust disc, and is currently considered to be one of the best known candidates for an extrasolar planetary system.

Recently, Lagage & Pantin (1994) have analysed an infrared image of the inner part of the dust disc of β Pic, showing that the dust is asymmetrically distributed and strongly depleted within 40 au of the star, which may be interpreted as indicating the possible presence of a planet orbiting the star. Additional evidence for a planet has been provided by *Hubble Space Telescope* (*HST*) images, which reveal an unexpected warp of the cleared zone of the disc (Villard & Burrows 1996). The presence of such a warp is thought to be due to at least one planet, not too dissimilar from Jupiter in size and orbit (Villard & Burrows 1996).

Further indirect evidence is furnished by visible and ultraviolet spectroscopic observations of this star, which show transient redshifted absorption lines of several ions (Hobbs

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et al. 1985). These phenomena are variable in both time and intensity, 200 events per year or even more being observed. These sporadic spectral signatures have been accounted for as being due to comets coming from the circumstellar disc (Ferlet, Hobbs & Vidal-Madjar 1987), releasing gas as they cross the stellar disc along the line of sight at distances of several (10–20) stellar radii or even less. These objects have been called 'falling evaporating bodies' (FEBs). This model seems to be the only one to explain all the observed spectral features (Vidal-Madjar et al. 1994). Other interpretations suggesting shells or photospheric activity cannot explain the variety of the observations (see for details Vidal-Madjar et al. 1994; also Sicardy 1994, and references therein). In a recent paper (Lecavelier des Etangs, Vidal-Madjar & Ferlet 1996), it has been shown that these FEBs also release large amounts of dust. In fact, this model has quantitatively accounted for the disc shape and the size of the dust particles.

A process involving a large number of comets falling near β Pic strongly resembles the process that occurred in the early Solar system (SS) during the planetary accretion phase. Therefore, assuming that the observed transient absorption lines are produced by this mechanism, the study of this process in the SS might serve to explain some important characteristics of the β Pic system.

2 ANALYSIS

What would an extrasolar observer expect to observe in the solar spectrum during the first stages of the SS evolution? In the SS, a cometary influx such as the one observed in β Pic occurred well before the formation of Jupiter and Saturn was finished, or when the outer giant planets had almost completed their accretion process.

The formation time-scale of Jupiter and Saturn is currently thought to be less than 10^7 yr, as suggested by the large amount of hydrogen present in their envelopes. Recently, Freudling et al. (1995) have found that in β Pic the gas-to-dust ratio is less than 10, indicating that most of the gas present in the protoplanetary nebula has been processed or expelled. This strongly suggests that, if planetary formation is proceeding in β Pic in a way similar to the SS, then Jupiter-like planets should have already been formed.

Once the outer planets had grown to masses several tenths of their current ones, they started to scatter unaccreted bodies well beyond their accretion zone. A large number of bodies from this population (the so-called 'outer planetary comets', OPCs) diffused inward, reaching the inner planetary system (Fernández & Ip 1983). During this process, a number of comets were also removed outward from the outer planetary region to distances $\gtrsim 10^4$ au, forming the so-called 'Oort Cloud'. Stellar and giant molecular cloud perturbations, as well as Galactic tides, can drastically reduce the perihelion distances of some of the members of the Oort Cloud, enabling them to reach the region of the terrestrial planets.

During the first $(1.5–2) \times 10^9$ yr since the SS formation, OPCs dominated the cometary flux rate in the region of the inner planets (Fernández & Ip 1983). Later, Oort Cloud comets became the dominant source. The time evolution of the number of comets reaching the region of the terrestrial planets per year (Fernández & Ip 1983), $F(t_9)$, may be approximated as

$$\log \frac{F(t_9)}{F(t_9=4.5)} = 5.53 \exp(-0.8434 t_9 + 0.06764 t_9^2) - 0.489, \qquad (1)$$

where t_9 is the SS age in units of 10^9 yr.

Other mechanisms related to orbital instabilities at mean-motion resonances (Beust & Morbidelli 1996) or secular resonances (if more than one planet exists in β Pic: Levison, Duncan & Wetherill 1994) have been recently proposed as a source for FEBs. The OPCs should work as another FEB source in which the perihelion distances may decrease suddenly, allowing FEBs to get closer than $\sim 2R_*$ (where R_* is the stellar radius) without being evaporated farther from the star in previous passages. This scattering of FEBs should make them deviate from a well-defined direction at least over the period covered by observations of FEBs in β Pic, indicating the position of the giant planet which should vary significantly on longer time-scales.

In order to compute the number of FEBs from this source per unit of time, we may use the collision rate of comets on to a given planet, which, in this case, is directly related to the number of comets with perihelion distances less than or equal to the planetary orbital radius. Actually, in the SS, collision rates have been computed (Olsson-Steel 1987), on the basis of a known population of 613 long-period comets. The relative collision probabilities with terrestrial planets (Olsson-Steel 1987), along with an assumed size distribution (Bailey & Stagg 1988), allow us to estimate that ~ 2.9 long-period comets of $\gtrsim 0.5–1$ km diameter get closer than 20 solar radii every year. The rate of the observed transient spectral lines on β Pic corresponds to the flux of comets in the SS at an age of $\sim 1.2 \times 10^9$ yr (cf. equation 1). Note that the age estimated by considering only OPCs should be taken as a lower bound for the age corresponding to a given cometary flux.

Extrapolating this age to β Pic is not straightforward, on account of the large variety of circumstellar discs around stars of similar age and mass. Thus this result should not be treated rigorously but should be taken as a possible indicator for a large stellar age. In making this calculation, we are not assuming that the planetary system around β Pic (if it exists) is similar to the SS, but we are employing the only information available at present. Of course, more general situations should be addressed in order to get a more reliable age estimate.

The present cometary flux rate in the inner SS is in fact dominated by short-period comets (Olsson-Steel 1987). Comets coming close to the Sun experience physical decay, releasing sublimated gases and dust particles. Several phenomena, such as the brightness and rate of sublimated mass decrease (Hughes & Daniels 1983), non-gravitational forces (Marsden & Sekanina 1971), and the fraction of short-period comets that have ceased to be observed (Kresák 1981), lead to average lifetimes of about 500–1000 revolutions for short-period comets. $L_{bol}(\beta \text{ Pic}) \sim 10 L_{bol}(\text{Sun})$, and therefore the sublimated mass rate in β Pic is expected to be nearly 10^3 times the one in the SS (Beust et al. 1989). Consequently, the observed spectral signatures are produced, within this scenario, by long-period comets or

OPCs reaching the inner portion of the disc for the first time.

Let us now investigate this problem in the framework of stellar evolution. A standard way to measure stellar ages is to compare the bolometric luminosity ($L_{\rm bol}$) and the effective temperature ($T_{\rm eff}$) with stellar evolution calculations. This allows us to gauge unequivocally the age of stellar clusters (see e.g. Clayton 1968), but not of individual stars (like β Pic), because the tracks followed by stars during their evolution in the $L_{\rm bol}$–$T_{\rm eff}$ (Hertzsprung–Russell, HR) diagram (HRD) may pass through the same point more than once.

Recently, Lanz, Heap & Hubeny (1995) carefully studied the spectrum of β Pic, concluding that $L_{\rm bol}=11.3\ {\rm L}_{\odot}$ and $T_{\rm eff}=8200$ K, with uncertainties of $\pm 3.5\ {\rm L}_{\odot}$ and ± 150 K, and deduced that the chemical composition is similar to that of the Sun. For such values, employing two sets of pre-main-sequence (PMS) (D'Antona & Mazzitelli 1994) and later evolutionary models (Van den Bergh 1985), they inferred a mass of $M=1.8\pm 0.1\ {\rm M}_{\odot}$, and two possible ages: 1.2×10^{7} and $\geq 3\times 10^{8}$ yr. However, we should note that the above-quoted sets of evolutionary calculations have been constructed by employing different physical ingredients (e.g. opacities). We shall show that a self-consistent treatment leads to different possible solutions for the age and mass of β Pic.

In order to cover the region of the HR diagram in which β Pic is located, we have computed the evolution of stars with masses from 1.6 to 2.0 ${\rm M}_{\odot}$ and solar chemical abundances ($X=0.70$, $Y=0.28$, $Z=0.02$ for the fractional mass abundances of hydrogen, helium and heavy elements respectively), starting from the PMS contraction up to near helium ignition. For this computation, we employed a code based on the Henyey technique, including a complete set of nuclear reaction rates (Fowler, Caughlan & Zimmerman 1975; Harris et al. 1983), and treating the evolutionary chemical abundances as in Arnett & Truran (1969). The equation of state that we employed is from Magni & Mazzitelli (1979), and the opacities have been taken, for $T\geq 6000$ K, from Iglesias & Rogers (1993), and for lower temperatures from Alexander & Ferguson (1994), who included the molecular contributions. Conductive opacities and neutrino emission processes have been computed as in Benvenuto & Althaus (1995). We have employed the Schwarzschild criterion for the onset of convection. In convective zones, the temperature gradient has been calculated according to the mixing length theory, and the mixing length has been taken to be equal to the pressure scaleheight.

In Fig. 1 we show the HR diagram for stars of 1.6, 1.7, 1.8, 1.9 and 2.0 ${\rm M}_{\odot}$ with solar chemical abundances. Note that the observational error box (the dotted rectangle in Fig. 1) is crossed by the hot boundary of the main sequence, showing that not all of the possible $L_{\rm bol}$ and $T_{\rm eff}$ for β Pic are consistent with the stellar evolution theory.[1] In Fig. 2 the $L_{\rm bol}$ versus age relationship for the above-cited models is depicted. The dotted line portions of the curves depict evolutionary stages inside the β Pic error box, representing possible solutions for its age and mass.

[1]Note, however, that this is strongly dependent upon Z; other values different from $Z=0.02$ would change the portion of the error box that is consistent with stellar evolution.

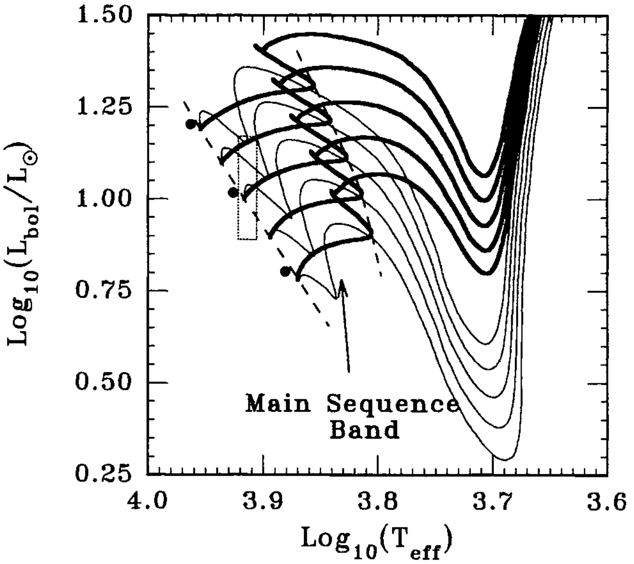

Figure 1. The HR diagram for stars (from bottom to top) of 1.6, 1.7, 1.8, 1.9 and 2.0 ${\rm M}_{\odot}$ with solar chemical abundances ($X=0.70$, $Y=0.28$, $Z=0.02$). The PMS evolution is denoted by thin solid lines, while thick solid lines represent the subsequent evolution. The boundaries of the main sequence are indicated with long-dashed lines, while the error box inside which β Pic should be located (Lanz et al. 1995) is shown by dotted lines. For the sake of comparison, we also show, with filled circles, the hottest points of the PMS evolution for stars of 1.6, 1.8 and 2.0 ${\rm M}_{\odot}$, calculated by D'Antona & Mazzitelli (1994).

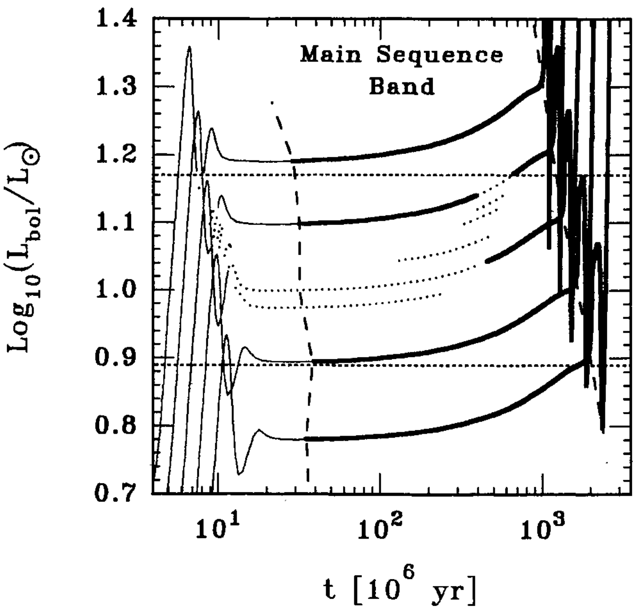

Figure 2. The logarithm of the bolometric luminosity versus the logarithm of the age for stars (from bottom to top) of 1.6, 1.7, 1.8, 1.9 and 2.0 ${\rm M}_{\odot}$. Solid thin and thick lines correspond to PMS and subsequent evolution, respectively, whereas long-dashed lines indicate the main-sequence boundaries. Horizontal short-dashed lines indicate the luminosities of the edges of the β Pic error box. Dotted lines represent evolutionary stages inside β Pic's error box, and thus are consistent with observations. In order to define this region better, we have also included results corresponding to objects of 1.766, 1.833, 1.866, 1.880 and 1.925 ${\rm M}_{\odot}$. For the last of these masses we have found no main-sequence evolutionary stage inside β Pic's error box.

Concerning the computation of PMS and later evolution, our results resemble those of D'Antona & Mazzitelli (1994) and Schaller et al. (1992) respectively. However, we should note that, in our calculations, the hot boundary of the main sequence is slightly cooler (see Fig. 1). For example, the $T_{\rm eff}$ of the 1.6-$M_\odot$ object is ≈ 2 per cent lower than the value computed by D'Antona & Mazzitelli (1994). This is mainly due to the inclusion of the updated opacities of Iglesias & Rogers (1993) and Alexander & Ferguson (1994), and a minute difference in the heavy elements content [$Z=0.019$ for D'Antona & Mazzitelli (1994) and $Z=0.02$ for us]. The shift of the hot edge of the main sequence decreases the portion of the error box that is compatible with stellar evolution theory, and makes the allowed ages somewhat smaller. Nevertheless, it should be noted that this is a rather small effect in view of the present uncertainties in the $L_{\rm bol}$–$T_{\rm eff}$ relation of β Pic.

Compared with the previous analysis of Lanz et al. (1995), the main advantage of our treatment lies in its self-consistency. Note that these authors stated only two (12×10^6 and $\gtrsim 3\times10^8$ yr) ages as possible for β Pic; however, our treatment shows that there is a continuum of possible ages corresponding to stars evolving inside the error box.

The possibility of the presence of planets around β Pic is strongly related to its age. Small ages ($\sim 10^6$ yr) preclude the existence of a planetary system, as it would not have had time enough to complete its formation. However, if the age of β Pic is $\gtrsim 10^8$ yr, planets may have already been formed (Lissauer 1993). Based on the difficulty of accounting for the presence of the dust disc for time-scales of $\sim 10^8$ yr (Sicardy et al. 1993), Lanz et al. (1995) suggested that the actual age of β Pic should be the smaller one, precluding the presence of mature planets around it (Beckwith 1995). Note that, if we accept the results of Lecavelier des Etangs et al. (1996) which indicate that the structure of the dust disc may be accounted for by the dust released by the sublimating comets, then the main argument of Lanz et al. (1995) favouring a small age for β Pic is no longer meaningful.

All our calculations do indicate a large age, at which outer giant planets should have almost completed their formation and the cometary flux near β Pic should be declining. All the evidence discussed in this paper is consistent with this, and clearly favours the presence of at least one planet orbiting near β Pic.

The estimation of stellar ages employing cometary fluxes should be treated with caution on account of the possible diversity of extrasolar planetary systems (Lissauer 1995; Wetherill 1996). This seems to be particularly relevant on account of the recent discovery of a Jupiter-like planet moving around 51 Pegasus in a close orbit (Marcy & Queloz 1995). However, a detailed study of the evolution of the cometary influx in more general situations than that in the early SS (in the sense of the work by Fernández & Ip 1983) might be useful in order to show the capability of this method.

Let us note that, if the transient absorption lines are a consequence of the process of formation of planetary systems, these lines may be employed to detect such formation processes in other stars. Such a type of search is already underway (see Lagrange-Henri et al. 1990).

It is difficult to anticipate whether planets with the estimated age of β Pic could be directly detected. Current estimates of planetary evolution (Burrows et al. 1995) predict them to be detectable in dust-free environments with forthcoming technology. However, the dust disc surrounding β Pic is far brighter than planets at wavelengths $\lambda \gtrsim 3$ μm (Artymowicz, Burrows & Paresce 1989). At shorter wavelengths, dust does not emit but (as planets) reflects stellar light, making planetary detection barely possible even in the presence of a centre-cleared disc (Lagage & Pantin 1994).

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