A&A 402, L5–L8 (2003)
DOI: 10.1051/0004-6361:20030369

Astronomy & Astrophysics

Letter to the Editor

A stream of particles from the β Pictoris disc: A possible ejection mechanism

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Received 5 September 2002 / Accepted 12 March 2003

Abstract. Recently, a stream of particles originating from the direction of β Pictoris, a young main sequence star surrounded by a dust disc, has been reported (Baggaley 2000). Standard mechanisms of particle ejection from a disc fail to reproduce the properties of this stream. We find that scattering by a giant proto-planet with properties taken from the literature is consistent with the observations. The fact that a straightforward ejection mechanism reproduces the data supports the identification of the particle stream's source with β Pic. Our work also indicates that protoplanetary dust discs form a potentially rich source of large interstellar grains, as widely detected in the Solar System.

Key words. circumstellar matter – meteors, meteoroids – planetary systems – stars: individual: β Pic

1. Introduction

Ever since its discovery the dust disc around β Pic has been a rich source of surprises, one of which is its anomalously high dustiness compared with other debris, or second-generation, discs (i.e. discs sustained by a collisional cascade of dust grains released by comets and/or planetesimals). The surprises also include the depletion of dust in the innermost part of the disc (Lagage & Pantin 1994) similar to that caused by Jupiter and Saturn in the Solar System (Liou & Zook 1999), global asymmetries and inner warps observed in the disc (Kalas & Jewitt 1995; Heap et al. 2000) and the so-called Falling Evaporating Bodies (analogues of comets in the Solar System; Beust et al. 1990). All of these observations point to the presence of one or more (proto-)planets in the disc.

One recent surprise has come from observations made with the Advanced Meteor Orbit Radar (AMOR) of meteoroids ablating in the Earth's atmosphere (Baggaley 2000). This unique facility (Baggaley et al. 1994) provides routine measurements of the heliocentric orbits of Earth-intersecting meteoroids down to limiting radii of about 20 μm and allows the identification of the source direction. Observations revealed the existence of a discrete dust stream whose source lies outside the Solar System. The source of the coherent stream was identified with β Pic which is only 2° from the observed influx direction measured with an uncertainty of 5° (Baggaley 2000). If correct, this discovery implies that in situ investigations of dust particles from an identified extra-solar source are possible.

These observations also present a considerable challenge, however, since the normally considered mechanisms of dust removal from the discs of main sequence stars cannot explain the origin of a dust stream with the observed characteristics: the particles are large (typical radii of about 20 μm), fast (they leave the β Pic system with a velocity of 25–30 km s^{-1}) and their mass loss rate may be up to 10^{-3} $M_{\oplus}$/yr (Baggaley 2000). In the standard picture for β Pic, mutual collisions break big particles into smaller ones, which are then swept out by stellar radiation pressure (Krivov et al. 2000). However, particles ejected by this mechanism are less than a few microns wide (Artymowicz 1988) and hence considerably smaller than the observed ones. Here we propose another ejection mechanism for the stream of particles from β Pic, based on their interaction with one or more (proto-)planets in the β Pic disc.

2. Ejection of material during planet formation

2.1. Solar system

Current theories of giant planet formation imply that, first, a solid core of a planet with a mass of about 10 $M_{\oplus}$ is formed. This takes place on time-scales of up to 10–20 Myr (Bodenheimer & Pollack 1986). When the core has grown sufficiently, it starts to accumulate gas from the protoplanetary disc. The relative velocities of the bodies in such a system are determined by their gravitational perturbations during close encounters and increase with the growth of the largest bodies. At some planetary embryo mass the highest velocities become sufficient for the small bodies to be scattered out of the system (Safronov 1969, 1972). Theoretical estimates suggest that during this stage up to 300 $M_{\oplus}$ were ejected completely out of the Solar System (Safronov 1972; Fernandez & Ip 1981), to which Jupiter contributed about 100 $M_{\oplus}$.

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2.2. β Pictoris

The formation of giant planets in other systems is expected to follow the same path, so that at some stage the growing planetary embryo scatters out the remaining material from which it was born. Having started the ejection, a giant planet continues to scatter all the bodies it encounters, but most of the disc mass is ejected during the first active period, which lasts on the order of 10 Myr (Fernandez & Ip 1981). As the typical life-time of a debris disc is 300–400 Myr (Habing et al. 1999), this means that 1 of about 30 to 40 main-sequence stars with discs is at this stage. We propose that in the young main-sequence star β Pic the dust disc is currently being cleared by a nascent planet.

The β Pic system is in many ways unique from among about 100 known discs and disc candidates around nearby main-sequence stars, so that it is likely to be in a relatively brief phase of evolution. Its low age of 20 ± 10 Myr (Barrado y Navascues et al. 1999) and high dustiness make it consistent with the late stages of planet formation. Recent observations of molecular hydrogen in the system support this idea. The remaining amount of gas, not more than ≈0.17 Jupiter masses, $M_{\rm J}$ (Thi et al. 2001), and probably much less (Lecavelier des Etangs et al. 2001; Richter et al. 2002) is insufficient to form a Jupiter-like planet, so that the accretion phase must be fairly advanced.

Let us estimate the minimum embryo mass required to initiate the ejection of other bodies from the disc. The mean relative velocity of bodies perturbed during their close encounters with a growing planetary embryo of mass $m_{\rm p}$ and radius $r_{\rm p}$ is

$$v_{\rm per} = \sqrt{Gm_{\rm p}/\theta r_{\rm p}}, \tag{1}$$

with G being the gravitation constant and θ a dimensionless parameter whose most probable value lies in the range 1–10 for Jupiter-like planets at the beginning of ejection (Safronov 1969, 1972). A particle or planetesimal is ejected from the system if its velocity

$$v_{\rm ej} = v_{\rm K} + v_{\rm per} \geq v_{\rm esc} = 1.4 v_{\rm K}. \tag{2}$$

Here $v_{\rm K} = \sqrt{GM_*/R}$ is the Keplerian circular velocity of the embryo moving around the star of mass M_* at a distance R. For β Pic ($M_* \approx 1.8\ M_\odot$), the ejection begins when the protoplanet, having a density of 1 g/cm^3, reaches the mass $\approx 5 \times 10^{-2}$–10^{-1} $M_{\rm J}$, if it is located at 3 AU, or $\approx 10^{-3}$–5×10^{-3} $M_{\rm J}$ at 30 AU. Analysing the warp in the inner disc of β Pic, Mouillet et al. (1997) derived the following relation between $m_{\rm p}$ and R: $(m_{\rm p}/M_*)(R/10{\rm AU})^2(t/5.2{\rm yr}) \approx 3000$, where t is the age of the system. Heap et al. (2000) introduced a scaling factor for a new estimate of the distance by Hipparcos and obtained 0.2–50 $M_{\rm J}$ for a planet located between 3 AU for the higher mass and 50 AU for the lower one (t = 20 Myr). This implies that the planet or planets must have initiated the scattering of smaller bodies out of the system.

Bodies with smaller perturbed velocities encountering a planet can enter nearly parabolic trajectories and end up at the periphery of the system, or be handed down to the inner regions (Fernandez & Ip 1981). The same mechanism is believed to have populated the Oort cloud of comets in the Solar System (Weissman 1990). Observational manifestation of this process in the β Pic system is offered by numerous and active Falling and Orbiting Evaporating Bodies (Beust et al. 1990; Lecavelier des Etangs 1999). They cannot have been active for a long time, independently suggesting that β Pic is in a transient evolutionary stage (Lecavelier des Etangs 1999).

3. Expected properties of the particle stream

Are there any grounds to expect particles ejected from the β Pic disc by forming planets to be registered at the Earth and can the ejection mechanism provide a possible explanation for their observed characteristics? In the following we search for an answer to these questions.

Bodies encountering a planet are predominantly ejected in the direction of the orbital motion of the planet, i.e. at small angles with respect to the orbital plane (Safronov 1972). The evidence suggests that the orientation of this plane is close to the orientation of the β Pic dust disc. Firstly, being born from dust in the disc, planets are anticipated to have low inclinations with respect to the disc plane. E.g. in the Solar System all the planets lie nearly in the ecliptic plane. Secondly, an inclination of only about 3°–5° to the mid-plane of the outer disc is derived by Mouillet et al. (1997). In its turn, the inclination of the dust disc around β Pic is less than 5° (Kalas & Jewitt 1995). Hence the orientation of the system in space is very favourable for detecting particles scattered out by a planet.

The initially strong periodicity of the number of ejecta directed towards Earth, caused by the predominant ejection along the direction of motion of the planet, is smeared away during their passage to Earth. The period of the alleged planet is $\lesssim$200 yrs for $R < 50$ AU, while it takes the particles an estimated 7×10^5 yrs to reach the Earth. Consequently, a dispersion in the velocities of the ejecta of 0.05% is sufficient to spread the ejected particles over all phases of the protoplanet's orbit. The real dispersion is likely to be much higher.

Note also that a particle with radius $r_{\rm d}$ = 20 μm (or bigger) leaves the system without interference from the gas when $M_{\rm g} \pi r_{\rm d}^2 \ll m_{\rm d}$, where $M_{\rm g}$ is the mass column density of the gas and $m_{\rm d}$ is the particle mass. For a 20 μm wide particle with a density of 2 g cm^{-3}, this requires that $M_{\rm g} \ll 5 \times 10^{-3}$ g cm^{-2}. The upper limit for the column density of gas in the β Pic disc is $\sim 10^{19}$ cm^{-2} for H (Freudling et al. 1995), which gives $M_{\rm g} \approx 2 \times 10^{-5}$ g cm^{-2}.

Baggaley (2000) found that the particles in the β Pic stream asymptotically reach a speed, $v_{\infty,\rm obs}$, of about 25–30 km s^{-1}. Can the proposed ejection mechanism produce such high observed velocities? We consider a planet with the parameter combination $(m_{\rm p}, R)$ deduced from the inner warp of the disc (Mouillet et al. 1997; Heap et al. 2000). The value of θ is small at the beginning of ejection (3 to 5 are typically taken for a nascent Jupiter) but increases with the growth of the embryo (Safronov 1969, 1972). It is also higher for planets further away from the star. Therefore we consider θ = 5, 30 and 50.

Table 1. Asymptotic speeds reached by particles ejected by a nascent planet from the β Pic system for different values of the parameter θ. The mass of the protoplanet, m_p, and the radius of its orbit are taken following Heap et al. (2000). The mass at 3 AU is taken from (1997), since a planet with the mass of 48 M_J derived by Heap et al. (2000) would be evident in radial velocity variations. Values in brackets are estimates corrected for radiation pressure, calculated assuming a ratio of radiation pressure to gravity $\beta = 0.1$.

$m_p[M_J]$	R [AU]	v_∞ [km s^{-1}]		
		$\theta = 5$	$\theta = 30$	$\theta = 50$
20	3	69	31	23 (29)
17	5	63	28	23 (26)
4.4	10	41	19	15 (16)
1.1	20	27	11	10 (10)

Velocities of particles scattered into hyperbolic orbits achieved asymptotically after leaving the system, v_∞, can be calculated using

$$v_\infty = \sqrt{v_{ej}^2 - v_{esc}^2} \quad (3)$$

and Eqs. (1) and (2). The obtained speeds v_∞ are given in Table 1. Our preliminary numerical simulations (Krivov et al., in preparation) suggest that, indeed, the case of higher θ is more realistic and the velocities of about 20–30 km s^{-1} are achieved for a rather massive ($\sim$15 – 20 M_J) planet located within 10 AU. Radiation pressure weakly affects particles of 20 μm, increasing their velocities by a few km s^{-1}. As an illustration, v_∞ for $\theta = 50$ is shown in Table 1 with and without radiation pressure.

Next we consider the question why, if the stream detected by Baggaley (2000) really comes from β Pic, no earlier evidence for, e.g., smaller particles has been found. The size distribution of particles in the β Pic system, although determined by somewhat different processes, is found (Krivov et al. 2000) to be similar to that in the Solar System at 1 AU from the Sun (Grün et al. 1985) with three distinct slopes depending on the size regime. The number of particles drops steeply with increasing size, with a power-law exponent of about 3.5, for grains smaller than the radiation pressure blow-out limit (a few microns for β Pic). It is markedly flatter for grains just above this limit, as their collisional destruction by smaller grains streaming outwards is more efficient than production. For grains bigger than tens of microns, the power-law exponent is again 3.5 or even higher. In the Solar System, the distribution for interplanetary grains bigger than about 100 μm approximately follows a^{-5} (Grün et al. 1985; Ishimoto 2000). With such a shape, the distribution has a local maximum at about 10 micron (supported by observational data – see, e.g., Krivova 2002); which is near the lower sensitivity limit of AMOR. For comparison, grains with sizes of a few hundred microns are at least 10^3–10^4 times less abundant. Hence we expect the particles detected by AMOR to mainly have sizes of 20–30 μm. The charge-to-mass ratio of such large particles is too low for their motion to be controlled by the interstellar or heliospheric magnetic field, unlike smaller grains. They are also not expected to be noticeably affected by the interstellar medium (Grün & Landgraf 2001).

Consider now small grains. Interstellar particles with radii smaller than $\approx$1 μm have also been detected in the Solar System (Grün et al. 1993; Landgraf et al. 2000) by the dust detectors on-board the Ulysses and Galileo spacecraft. From the measured flux of large and small particles (Landgraf et al. 2000) as well as the spectrum of particle sizes we estimate that the discrete source identified by AMOR should give at most one or two impacts per year, whereas the pointing accuracy of the instrument of $\pm 70°$ (Landgraf et al. 2000) would make the identification of the stream direction impossible. In addition, particles smaller than a few microns are intensively destroyed in collisions when streaming outwards across the disc, while most larger grains should escape (Krivov et al. 2000).

A nascent Jupiter-like planetary embryo can, according to estimates for the Solar System (Safronov 1972), eject up to 100 $M_\oplus$ in solid material out of the disc. A planet which is more massive and/or closer to the star can eject much more material. For $\sim$100 $M_\oplus$ ejected during 10^7 years, the average ejection rate is $\sim 10^{-5}$ $M_\oplus$/yr. Unfortunately, due to high uncertainties in system calibration, no precise value of the observed mass-loss-rate can be made. A very crude estimate gives an upper limit of $\sim 10^{-3}$ $M_\oplus$/yr (for ejection in a disc with a half-opening angle of $\sim 7°$ and at a distance of 19.3 pc; Baggaley 2002, private communication), which is still larger than our mechanism suggests. The two values may nevertheless be compatible if the high ejection rate currently observed does not stay constant for the full 10^7 years, but peaks over a relatively short interval of roughly 10^5 yrs. This is in good agreement with the diffusion time scale for planet-crossing bodies for a planet with the properties suggested by our velocity analysis as well as by previous estimates (Gaidos 1995). We stress, however, that both theoretical and observed values are too uncertain for accurate comparison and more work is needed.

4. Large IS particles in the Solar System

Ejection by nascent giant planets may also be an important mechanism for injecting into the interstellar (IS) medium the large dust particles detected in the Solar System (radii up to several micron for in situ experiments and more than 10 μm for radar measurements, Grün et al. 1993; Taylor et al. 1996). These radii are one to two orders of magnitude bigger than the expected average size of IS grains (Grün & Landgraf 2000, 2001). Particles with large sizes are also deduced from interstellar emission at submillimeter wavelengths (Kim & Martin 1996). Particles cannot grow to such sizes in the environments of red giants, believed to be the main suppliers of IS dust, or in the IS medium (Whittet 1992). Protoplanetary dust discs form a potentially rich source of large IS grains, but no mechanism was known for ejecting the required particles (Grün & Landgraf 2000).

Recent observations of extra-solar planets and dust discs around main-sequence stars indicate that both phenomena are quite common. Let us assume that all main-sequence stars pass through a β Pic-like stage and one Jupiter-like planet is formed per star. Although only 5% of solar-type stars have so far been found to have a giant planetary companion (Mayor & Santos 2001), these are mostly massive planets located very close to the star and are thus much more efficient in ejecting material than Jupiter was. Also, smaller and more distant planets cannot currently be detected, implying that 5% of stars is a lower limit. Finally, multiplanetary systems may be quite common (Mayor & Santos 2001). Therefore, our "one-planet per star" approximation can be used for crude estimates. Then assuming that 100 $M_{\oplus}$ is ejected per planet we obtain that up to 1000 $M_{\oplus}$/yr may be injected into the galactic disc due to this mechanism. This corresponds to 10% of the total dust injection rate by all sources (Whittet 1992). Although the winds of cool stars are the dominant source, grains cannot grow to more than a few tenths of a micron in the envelopes of these luminous stars, being swept out by the strong radiation pressure before that (Whittet 1992).

Whereas mean lifetimes of typical (sub-micron sized and smaller) IS grains are $\sim 10^8$–10^9 yrs (Whittet 1992), the big particles we discuss survive at least 100 times longer (Grün & Landgraf 2000). Taking $\sim 10^{10}$ yrs for their average lifetimes, we find that the mass-density of grains ejected from protoplanetary discs into the galactic disc is $\sim 2\times 10^{-27}$ g cm^{-3}, within an order of magnitude of 1.78×10^{-26} g cm^{-3} obtained from spacecraft measurements (Grün & Landgraf 2000). Interestingly, one of the directions from which the IS meteoroids come into the Solar System is associated with the motion of the Solar System relative to nearby A-type stars and was interpreted as being due to particles ejected from debris discs (Taylor et al. 1996). Our estimate therefore suggests that for the large grains the clearance of dust discs such as that of β Pic may be an important, possibly even the main, source.

5. Concluding remarks

We have pointed out that the ejection of bodies out of the β Pictoris system during the late stages of planetary formation through scattering by a Jupiter-like protoplanet with properties taken from the literature (Mouillet et al. 1997; Heap et al. 2000) can produce particle speeds and sizes similar to those in the stream detected and analysed by Baggaley (2000). The relatively low mass of dust particles remaining in the β Pic disc (several Moon masses; see e.g. Lecavelier des Etangs 1999) suggests that the planet has already scattered out most of the material, which is not surprising if one takes into account that particles registered by AMOR must have left the disc almost 1 Myr ago.

The theory underlying the present work was originally developed to explain the formation of the Oort cloud of comets surrounding our own planetary system by the scattering of particles and larger bodies by the nascent giant and outer planets. By analogy to the Solar System we hence expect that β Pictoris is currently building up its own Oort cloud. This idea is supported by the observations of the Falling Evaporating Bodies (Beust et al. 1990). The fact that theory is compatible with the observations also supports the identification made by Baggaley (2000) of β Pic as the origin of the dust stream. These particles thus provide the unique possibility of carrying out in situ measurements of the material composing a young stellar system. A need for better estimates of the particle flux remains. Also, the present simple estimate should be followed by a numerical simulation.

Acknowledgements. We are grateful to W. J. Baggaley for providing us with information on his instruments and data. We also thank A. V. Krivov for extensive discussions, E. Grün for helpful comments and A. Lecavelier des Etangs for suggestions that improved the manuscript.

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