Planetary migration and sources of dust in the $\beta$ Pictoris disk

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Abstract. The dust disk around $\beta$ Pictoris must be produced by collision or by evaporation of orbiting Kuiper belt-like objects. Here we extend the already proposed Orbiting-Evaporating-Bodies (OEB) scenario in which the disk is a gigantic multi-cometary tail supplied by slowly evaporating bodies like Chiron. We show that the number of these OEBs must be several tens of millions, and that this is consistent with the number of bodies needed to explain the presence of CO and C$^1$ in the gaseous disk.

We explore some possible origin of the required perturbation on the OEBs. If dust is produced by evaporation, a planet with an eccentric orbit can explain the observed asymmetry of the disk, because the periastron distribution of the parent bodies are then expected to be non-axisymmetric. Following Malhotra (1995), we investigate the consequence for the Kuiper belt-like objects of the formation and the migration of an outer planet like Neptune in Fernández’s scheme (Fernández 1982). We find that bodies trapped in resonance with a migrating planet can significantly evaporate, producing a $\beta$Pictoris-like disk with similar characteristics like opening angle and asymmetry.

We thus show that the $\beta$ Pictoris disk can be a transient phenomenon. The circumstellar disks around main sequence stars can be the signature of the present formation and migration of outer planets.

Key words: stars: $\beta$ Pic – circumstellar matter – planetary systems

1. Introduction

1.1. The $\beta$ Pictoris disk

Since their discovery by IRAS in the 80’s (Aumann et al. 1984), we have now some information about the infrared excess Vega-like stars and their circumstellar dusty environment. Our knowledge come essentially from the infrared observations from which can be extracted the spectral energy distribution of the thermal emission (Sylvester et al. 1996), which constrains the particle size (e.g., Habing et al. 1996) and total dust mass (Zuckerman & Becklin 1993). Silicate band emissions have also been detected around some of these stars (Skinner et al. 1992, Fajardo-Acosta et al. 1993, Knacke et al. 1993, Fajardo-Acosta & Knacke 1995).

However among these infrared excess stars, $\beta$ Pictoris has a very peculiar status because images have shown that the dust shell is in fact a disk seen edge-on from the Earth (Smith & Terrile 1984) and have given unique information on the dust distribution. The disk morphology and the inferred spatial distribution of the dust have been carried out in great details (Artymowicz et al. 1989, Kalas & Jewitt 1995). The morphological properties (see Lecavelier des Etangs et al., 1996, hereafter LVF) can be summarized as follows:

First, the gradient of the scattered light follows a relatively well-known power law. But the slope of this power law changes at about 120 AU from the star (Artymowicz et al. 1990, Golimowski et al. 1993). The question of whether this change is abrupt or not is still open (Mouillet et al. 1997a). Second, the disk has an inner hole with a central part relatively clear of dust (Backman et al. 1992, Lagage & Pantin 1994). In the third dimension, the disk is a “wedge” disk: the thickness increases with radius (Backman & Paresce 1993, Lecavelier des Etangs et al. 1993). More surprisingly, the disk is not symmetric (Smith & Terrile 1987): five different asymmetries have been described by Kalas & Jewitt (1995) who showed that the disk presents asymmetries in size, brightness and width, together with butterfly and wing-tilt asymmetries. All these asymmetries except the last one show that the disk is not axisymmetric. An intriguing property is that, despite the asymmetries in brightness and width, the total brightness integrated perpendicular to the mid-plane seems to be, on the contrary, symmetric. Finally, the inner part of the disk (∼ 40 AU) seems to be warped. This warp has been well-explained by Mouillet et al. (1997b) as due to an inclined planet inside the disk.

As the dust particle life-time is shorter than the age of the system, one must consider that the observed dust
is continuously resupplied (Backman & Paresce 1993). In order to explain the origin of the dust in the β Pictoris disk and these well-known morphological properties, we have proposed the Orbiting-Evaporating-Bodies model (hereafter OEB, see LVF).

After a brief summary of the OEB scenario (Sect. 2), and a counting of these OEBs (Sect. 3), we present plausible origin of the needed perturbation on the parent bodies in Sect. 4 and 5. We will see that the β Pictoris disk can be a natural consequence of the formation of Neptune-like outer planets. The conclusion will be found in Sect 6.

2. Summary of the Orbiting-Evaporating-Bodies scenario

The observed dust is continuously resupplied. Two mechanisms can produce dust in this low density disk: collision or evaporation of kilometer-sized parent bodies (Weissman 1984). In both cases, because of the radiation pressure, the particles ejected from the parent bodies follow very eccentric orbits whose eccentricity is related to the grain size (Burns et al. 1979). If we assume a zero-order model of a narrow ring of bodies producing dust, the particles are then distributed on a disk-like structure presenting three morphological similarities with the β Pictoris disk. First, the central region of the disk is empty of dust, its limit corresponds to the inner radius of the parent bodies’ orbits. Second, this zero-order model disk is open because the distribution of the particles inclinations are the same as that of the parent bodies. Last, the dust density is decreasing with the distance to the star, moreover this density distribution follows a power law. Consequently, if seen edge-on from the Earth, the radial brightness profile along the mid-plane of this disk follows also a power law: \( F(r) \propto r^{-\alpha} \) (LVF).

We can conclude that a ring of parent bodies on circular orbits can naturally produce a disk with an inner hole, which is open, and if seen edge-on, the scattered light distribution follows a power law.

But the slope of this power law in the β Pictoris disk is observed to be \( \alpha \sim 4 \) (Kalas & Jewitt 1995). To explain this distribution with the assumption that the parent bodies remain in a narrow ring close to the star, a large quantity of small particles is needed (LVF). To solve this, we noticed that if a parent body of size \( \gtrsim 10 \) km produces dust by evaporation and is located at large distances, it produces only small particles. Indeed, if the evaporation rate is small enough, there is a cut-off on the maximal size of the particles which can be ejected from the body gravitational field by the evaporating gas. This slow evaporation and peculiar particle size distribution is observed in the Solar System around Chiron (Elliot et al. 1995, Meech et al. 1997).

In LVF, it has been shown that if some bodies migrate inward from the outer system, the migration rate is the key parameter which defines the distribution of the dust produced by the evaporation of these bodies. We find that the migrating rate must be \( 10^{-5} \) to \( 10^{-7} \) AU per year in order to correspond to the distribution observed around β Pictoris beyond 100 AU.

Several arguments are in favor of this scenario in the case of the β Pictoris disk. First, it is obviously easy to explain any asymmetry even at large distances, because a planet in the inner disk (on eccentric orbit) can have influence on the distribution of nearby parent bodies, and this non-axisymmetric distribution is projected outward by the particle on very eccentric orbits. Second, this also explains the disk brightness distribution. This distribution is reported in all published images since the first image by Smith & Terrile (1984) and is unsatisfactory left without explanation. Of course, as shown in LVF, the CO/dust ratio is one of the arguments which is in favour of the OEB scenario.

Finally, the connection between the inner radius of the disk and evaporation limit is a direct consequence of the OEB scenario because the periastron distances of the particles are similar to the periastron of the parent bodies. Any hypothetical planet located at this limit is no more needed to explain the presence of the inner void in the disk.

3. The number of Orbiting-Evaporating-Bodies

Until now, the OEB was described in a qualitative manner. We do not think that this is a major problem to this model. For any model of the dust origin, the qualitative aspects (dust distribution, morphology, grains properties,...) and observational prediction are required to validate it. Here to become more quantitative, we have just to evaluate the number of parent bodies corresponding to the production rate inferred from the total mass and the dust life-time. Finally, the last point will be to check that it is a reasonable value.

3.1. Bodies producing the observed CO

Whatever be the origin of the dust, the presence of CO is undisputed (Vidal-Madjar et al. 1994). We do not see any other process than evaporation to produce it. This gives a strong lower limit on the number of bodies which are now evaporating.

If we take an evaporation rate of CO: \( Z_{CO} \sim 10^{19} \) m\(^{-2}\)s\(^{-1}\) (see Fig. 3 of LVF) from a body with a mean radius \( \bar{R} \sim 20 \) km as given by the numerical simulation of the OEB model, this gives an evaporation rate per body of \( Z_{body} = 4\pi \bar{R}^2 Z_{CO} \sim 5 \times 10^{28} \) body\(^{-1}\)s\(^{-1}\). This rate is similar to the rate of the CO production observed on the Hale-Bopp comet at more than 6 AU from the sun (Biver et al. 1996, Jewitt et al. 1996) and has been qualified as “enormous”, because it is the same as for the comet Halley at 1 AU. Finally, \( N_{CO} \) the number of bodies (with
a typical radius of 20 km) now evaporating CO around β Pictoris must be
\[
N_{\text{CO}} = \frac{M_{\text{CO}} \tau_{\text{CO}}}{Z_{\text{body}} \mu_{\text{CO}}} \approx 6 \cdot 10^7
\]  
(1)

where \( \mu_{\text{CO}} \) is the molecular weight, \( M_{\text{CO}} = 7 \times 10^{20} \text{kg} \) is the total mass of CO in the disk (\( A \)), and \( \tau_{\text{CO}} = 2 \cdot 10^{-10} \text{s}^{-1} \) is the photodissociation rate of CO (Van Dishoeck & Black, 1988) destroyed by the UV interstellar background (the stellar extreme ultraviolet flux is very low and negligible).

This number is extremely large but unavoidable because CO is observed. It can be larger if the evaporation rate or the typical radii of the bodies are smaller. Even with the lower limit on the mass of CO given in \( A \) we still have to accept that the number of bodies now evaporating around β Pictoris and producing the observed CO must be in the order of tens of millions.

3.2. Bodies producing the dust

We can also roughly evaluate \( N_{\text{OEB}} \), the number of bodies necessary to produce the outer dust disk, if this disk is produced by evaporation of CO like in the OEB scenario. This number of OEB is
\[
N_{\text{OEB}} = \frac{M_d t_d^{-1}}{Z_{\text{body}} \mu_{\text{CO}} \phi_{\text{dust}/\text{CO}}}
\]  
(2)

where \( M_d \) is the mass of the dust disk, \( t_d \) is the dust lifetime, \( \varphi \) is the mass ratio of the dust effectively kept in the disk to the dust produced, and \( \phi_{\text{dust}/\text{CO}} \) is the mass ratio of dust to CO. We assume that the disk is about one lunar mass (\( M_d \approx 7 \cdot 10^{22} \text{kg} \)). The dust life time (\( t_d = 10^4 \text{yr} \)) is taken from Artyomowicz (1997)\(^1\). One can evaluate \( \varphi \approx 0.1 \). \( \phi_{\text{dust}/\text{CO}} \) is very uncertain: we use the recent value given by Sekanina (1996) on the comet Hale-Bopp observed at more than 6 AU from the Sun, and we assume that \( \phi_{\text{dust}/\text{CO}} \gtrsim 10 \). Finally we obtain:
\[
N_{\text{OEB}} \approx 9 \cdot 10^7 \left( \frac{M_d}{7 \cdot 10^{22} \text{kg}} \right) \left( \frac{t_d}{10^4 \text{yr}} \right)^{-1} \left( \frac{\phi_{\text{dust}/\text{CO}}}{10} \right)^{-1}
\]  
(3)

We see that, within the uncertainties, this number has the same order of magnitude as the number derived above in Eq. 1. As in Eq. 12 of LVF, this shows that the mass of dust driven by CO around β Pictoris is consistent with the total mass of dust in the outer part of the disk.

3.3. Conclusion

These \( \sim 10^7 \)–\( 10^8 \) objects must be compared to the \( 10^8 \)–\( 10^9 \) objects believed to be present between 30 and 100 AU from the Sun as the source of the Jupiter Family Comets (Duncan & Levison 1997, Morbidelli 1997). If we consider that these bodies have a radius of about 20 km as given by the models presented in LVF or given by the models of Sect. 3, this corresponds to about an Earth mass. This is well below the mass needed to supply the β Pictoris disk only by collision (30 Earth mass is needed according to Backman et al. 1995). Evaporation requires less mass of parent bodies, provided that some process is able to start the evaporation. As we will see in Sect. 4, a phenomenon believed to have occurred in the young Solar System can explain this evaporation.

3.4. β Pictoris a transient phenomenon?

It could be difficult to imagine that \( \sim 10^8 \) bodies have always been active for \( \sim 10^8 \) years. Only considering the observed CO gives that during \( 10^8 \) years, \( M_{\text{CO}} \times 10^8 \text{years} \times \tau_{\text{CO}} = 20M_\text{Earth} \) of CO must have been evaporated! It seems unlikely that this large number of bodies have been active since the birth of the system. This gives evidence that either that β Pictoris is very young (but already on the main sequence, which gives a lower limit on the age of \( \gtrsim 10^7 \) years (Crifo et al., 1997, see also discussion in Vidal-Madjar et al., 1998) or that β Pictoris must be a transient phenomenon. There is in fact no reason to believe that the β Pictoris system was always as dusty as observed today. Of course, the idea that this disk is not transient is a consequence of any model of collisional erosion from asteroid to dust. But with other scenarios, we can easily imagine that a particular phenomenon occurred recently, and that the density of the β Pictoris disk must be significantly smaller during the quiescent phase of simple collisional erosion during which the density can be similar to the characteristic density of the more common Vega-like stars.

4. The origin of the Orbiting-Evaporating-Bodies

Since the OEBs are able to explain some important aspects of the observations, possible origin of these OEBs, or more exactly the perturbations necessary to explain their evaporation, have to be explored. Indeed, evaporation takes place only when a body is formed beyond a vaporization limit of a volatile and is then relocated inside this limit. In fact, the “relocation” can have different meaning for an object on a keplerian orbit. It can be a simple variation of its semi-major axis or an increase of its eccentricity. In any case, the most important is certainly the periastron where most of the evaporation can take place. In fact, the beginning of evaporation is equivalent to a decrease of the periastron distance. Here we

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\(^1\) The dust lifetime used here is different from the \( 10^6 \) years assumed in LVF and taken from Backman & Paresce 1993. The discrepancy comes from a different evaluation of the normal optical depth of the disk given by Artyomowicz et al. (1989) and Backman et al. (1992). Anyway, these values are within the uncertainties of this rough calculation, and the same result could also be obtained with the life-time given by Backman & Paresce, if \( \phi_{\text{dust}/\text{CO}} \), the mass loading of the CO gas flow by dust is smaller than assumed here.
present some plausible origins of this decrease. The crucial points will be the possibility to explain the observed dust distribution, and some properties like the opening angle or the asymmetries.

In all the simulations presented here and in the next section, we use the mass of β Pictoris: \(M_\star = 1.8M_\odot\) (Crifo et al. 1997).

### 4.1. Perturbation by several planets

As already mentioned in LVF, it is very surprising that if the OEBs are supposed to migrate slowly inward from large distances, the speed of the evolution of the OEBs’ orbits (decreasing of their semi-major axis) is similar to the estimated motion of the Kuiper belt objects in the Solar System just beyond Neptune between 30 and 40 AU (Torbett & Smoluchowski 1990). This chaotic motion is due to the perturbation by the four giant planets of the Solar System and mainly Neptune. If several planets are present inside the evaporation limit with the last one close to this limit, similar motion can occur around β Pictoris. For example, if the last planet was at 20 AU, it would excite putative bodies just beyond and supply a β Pictoris-like disk with CO₂ as the main volatile; the same can be concluded for a planet around 100 AU with CO as the main volatile.

Here the asymmetry can simply be due to an eccentric orbit of the perturbing planet. For instance, one major planet on an eccentric orbit can cause a modulation of the precessing rate of the periastron of the OEBs. It is thus well-known that the distribution of the perihelion of the asteroids in the Solar System is not axisymmetric, and is closely related to the Jupiter longitude of the perihelion (Kiang 1966). The density of asteroids with the same longitude of perihelion as Jupiter is thus \(\sim 2.5\) times larger than that with perihelion in opposite direction. This is simply because when the periastron of an asteroid is located at 180 degrees from the periastron of Jupiter, the precessing rate is quicker and the density is smaller.

Such an effect would obviously cause an asymmetry in a disk if it is produced by evaporation of bodies with a distribution of periastron perturbed in this way. As the dust is mainly produced at the periastron of the parent bodies and principally observed during the apoastron, the part of the disk at 180 degrees from the periastron planet periastron could be more dense.

For example, we have evaluated the distribution of the periastron of a belt of bodies between 70 and 90 AU perturbed by a massive planet (mass \(M_p = 3 \cdot 10^{-4}M_\odot = 1.7 \cdot 10^{-4}M_\star\)) with an eccentricity \(e_p = 0.05\) and a semi major-axis of \(a_p = 30\) AU (Fig. 1). We find that, with bodies’ inclinations between 0 and \(7\) degrees and eccentricities between 0 and 0.12 (\(i^2 = e^2\), with \(i\) in radians), the density of bodies with same longitude of periastron as the planet is \(\sim 3\) times larger than that in the opposite direction (Fig. 2). This value of the ratio does not depend on the distance but is smaller if the bodies’ eccentricities are larger. As a conclusion, a planet on an eccentric orbit can be responsible for asymmetry in the distribution of the orbital parameter of the parent bodies of dust disks, and thus creates asymmetry in the observed disk if produced by evaporation of the parent bodies at periastron.

In the scenario of chaotic motion due to several planets, the β Pictoris disk is not a transient phenomenon but quiescent, the number of parent bodies already evaporated from the beginning of the process must be very large. However, catastrophic scenario can also be developed. As we will see, the β Pictoris disk can be a transient phenomenon.

### 4.2. A “cat-planet”

For two years, planets have been indirectly discovered through radial velocities measurements. These planets have very unexpected properties, with giant planets very
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5. Resonances with a migrating planet.

We develop now the most promising possible origin for the OEBs.

We propose a possible origin of the OEBs as an extension of the ideas of Fernández & Ip (1996), who showed that the outer planets migrated by several AU during their formation. As the time of motion is few hundreds of million years, it is likely that a similar phenomenon takes place around the young main sequence stars, around which circumstellar disks have been observed (10^8 years is about the age of \( \beta \) Pictoris and \( \alpha \) PsA). Here, we evaluate the dynamical consequence of the outer planet migration on the “planetesimals”, and particularly on the evolution of their orbits, the resonance trapping, and the possible evaporation.

5.1. The formation of Uranus and Neptune

It is now generally accepted that the formation of the Solar System could be divided into several stages starting with the accretion of Jupiter and Saturn in the gaseous solar nebula, and then followed by the accumulation of the terrestrial planets and the two outer planets, Uranus and Neptune (Lissauer 1993). But the formation of the outer planets of the Solar System raises a lot of problems in particular the problem of time scales: the planetesimal...
Mean values are given (solid lines) with Kuiper-like “pigeons-bodies” perturbed by a “cat-planet”. eccentricity \(e\) Fig. 3. A. Lecavelier des Etangs: Planetary migration and sources of dust in the \(\beta\) Pictoris disk. The planet has a mass \(M_p = 10^{-4} M_\odot\) = 5.6 \(\cdot\) \(10^{-5}\) \(M_\odot\), an eccentricity \(e_p = 0.95\) and a semi-major axis \(a_p = 300\) AU (and consequently periastron \(q_p = 15\) AU, and apoastron \(Q_p = 585\) AU).

The semi-major axis of the “pigeons-bodies” remain roughly constant, but their eccentricities increase and their periastrons decrease at a rate of about \(10^5\) AU per year. These bodies can thus produce dust by evaporation. As expected for the \(\beta\) Pictoris disk, they produce only small particles because they will be exhausted before the periastron is small enough for the gas drag to be able to eject the larger particles. Note that the inclinations significantly increase to several degrees, this is the same order as the opening angle of the \(\beta\) Pictoris disk.

\[
\begin{align*}
\text{accumulation time scale must be reasonably short, in any case shorter than the age of the Solar System itself (Lissauer 1987).}
\end{align*}
\]

Several solutions have been proposed to explain the accumulation of a large number of planetesimals into planets at several tens of AU, where the revolution periods are very large. For example, it has been proposed that the planet embryos could be driven by gas drag.

A smart solution has been proposed by Fernández (1982) who suggests that the accumulation and scattering of a large number of planetesimals is the origin of the migration of the outer planets during their formation. This migration is essentially due to the exchange of angular momentum between Jupiter and the proto-Uranus and proto-Neptune, via the accretion and gravitational scattering of planetesimals, the orbit of Jupiter loses angular momentum and shifts slightly inward, while those of Saturn, Uranus and Neptune move outwards, by several AU for Uranus and Neptune. This model successfully explains the formation of the two outer planets of the Solar System, in short time scale (\(2 \cdot 10^8\) to \(3 \cdot 10^8\) years), their mass and their actual position (Fernández & Ip 1996). Moreover, in this scenario, the sharp cutoff of planet mass at Neptune’s distance is due to the orbital expansion of the proto-Neptune, that allowed it to accumulate bodies from a wide zone of the proto-planetary disk.

The consequences of this scenario on the structure of the outer Solar System has been investigated by Malhotra (1993, 1995) who showed that this also explain the particular orbit of Pluto with large eccentricity and inclination, and its resonance with Neptune. In short, Pluto is trapped in the orbital commensurability moving outward during the expansion phase of Neptune’s orbit. The consequences on the Kuiper belt have also been analyzed (Malhotra 1995) and it has been demonstrated that the outward migration of Neptune can explain the fact that numerous Küiper belt objects are observed in Pluto-like orbit in 2:3 resonance with Neptune.

\[
\begin{align*}
\text{5.2. Planet migration and perturbation on parent bodies.}
\end{align*}
\]

Here we propose to extend this work to evaluate the link between the migration of outer planets and the \(\beta\) Pictoris-like circumstellar disks for which we know that the age is similar to the time scale of formation of these planets. Following Malhotra, we numerically investigate the consequence of the migration of the planets in the Fernández’s scheme on the dynamical evolution of the planetesimals, and their possible trapping in resonant orbits which allow evaporation of frozen volatiles.

For simplicity we consider only one outer massive planet supposed to suffer an exchange of orbital angular momentum as a back-reaction on the planet itself of the planetesimal scattering in the process of clearing the inner planetary region of residual planetesimals. Of course, at least a second inner planet must be there, in particular if the outer is migrating outward. Here, we consider only the principal outer perturbing planet which is supposed to migrate because of a force equivalent to a drag force decreasing with time: \(F_D \propto e^{-t/\tau}\), where \(\tau\) is the characteristic time of the migration. We only consider the effect of this migration on the outside bodies. CO is the only volatile considered for now.

We first look at the evolution of the orbits of a swarm of planetesimals (test particles). These bodies are swept by the resonances migrating simultaneously with the planet; we will check if they are trapped in one of these resonances and begin to migrate with it. Then, we evaluate if the resonant bodies can start to evaporate and produce dust.
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5.2.1. Resonance trapping

In fact, if the migrating planet is moving inward, the planetesimals are not permanently trapped in the resonances. Their semi-major axis remain unchanged and their eccentricities are only slightly increased. Consequently, the decrease of the periastron distance is too small to allow the volatiles to evaporate.

On the contrary, if the planet is moving outward, as given by the results of Fernández & Ip (1996) which show an expansion of the Uranus and Neptune orbits, a fraction of bodies can be trapped in resonances. Their semi-major axis and eccentricities increase significantly and the net result is a decrease of their periastron. If \( q_i, q_f, a_i \) and \( a_f \) are respectively the initial and final periastron distances and semi-major axis of the body, we have \( q_f/q_i \sim (1 - \sqrt{\ln a_f/a_i}) \). Thus \( q_f/q_i < 0.75 \) as soon as \( a_f/a_i > 1.1 \). As soon as a body is trapped in the resonance, the ratio of the final to the initial semi-major axis is the same for the body as well as for the planet. The decrease of the periastron of the body can be significant even if the planet’s semi-major axis is increased by only ten percent. This can start the evaporation of trapped bodies.

5.2.2. Evaporation

We have tested several configurations of outward migration and have evaluated the effect on planetesimals in the zones swept by first order resonances. We have arbitrarily considered only one planet starting from an initial semi-
The mass of the planet has been taken between Jupiter and Saturn mass. A less massive planet gives less efficient trapping. The eccentricity of the planet allows to test the possible influences on the asymmetry of the dust disk produced by the bodies trapped in “evaporating orbit”.

The conclusion of several test simulations can be summarized as follows:

- The 1:2 resonance is a very efficient resonance for trapping, even with a very fast migration ($\tau \sim 10^6$ years). But the variation of the periastron distance is too small to allow the evaporation ($\Delta q = q_f - q_i \approx -10$ AU).
- The 1:3 resonance is efficient if $\tau \gtrsim 10^7$ years and can give a large decrease of the periastron ($\Delta q \approx -30 - -40$ AU). But with a planet eccentricity of 0.05, no azimuthal asymmetry has been observed on the distribution of the periastron of the trapped bodies. Finally, there is no change in the distribution of the inclination which remain low.
- The 1:4 resonance give interesting results presented in Fig. 4 and 5. The trapping has been found to be efficient with rather extreme parameters: the mass of the planet must be $M_p \gtrsim 0.5 M_J$, where $M_J$ is the mass of Jupiter, the migration rate must be low ($\tau \gtrsim 5 \cdot 10^7$ years). The eccentricity of the planet has been taken to be 0.05. With these conditions, 19/500 bodies have been found to be trapped in the 1:4 resonance, and the periastron decreased by $\Delta q \approx -40$ AU. A significant increase of the inclination has been observed after few $\tau$ as well as a large asymmetry in the distribution of the periastrons longitude.

5.3. Time evolution of the disk density

As the dust life-time is very short ($t_d \sim 10^4$ yr in the $\beta$ Pictoris disk but also $t_d \sim 10^6$ yr around $\alpha$ PsA) and shorter than the stellar ages, the density of dust observed around the main sequence stars is directly related to the actual production rate of dust.

The time variation of the dust production rate, and consequently of the disk density, have been evaluated in the simulations described in Sect. 5.2. Fig. 4 shows the production as the function of time for the 1:4 resonance. The production of dust occurs between $3 \cdot 10^7$ and $7 \cdot 10^7$ years which is very consistent with the estimated age of $\beta$ Pictoris (Criso et al. 1997). We also conclude that the dust production rate by evaporation is transient and can be large during phase during which the bodies trapped in the resonances are entering in the evaporation limit. The $\beta$ Pictoris disk can be in such a state while other Vega-like stars are in quiescent phase.

5.4. Asymmetry

If the bodies are trapped in a resonance with a planet on eccentric orbit, there can be an asymmetry in the distribution of the periastron as already seen in Sect. 4.4. For example, the Fig. 4 gives the dust production rate by the bodies trapped in the 1:4 resonance with a planet on an eccentric orbit ($e_p = 0.05$). The production rate is larger in the direction of the periastron of the planet than in the opposite direction. The disk thus produced must be asymmetric with a larger density in the direction of the apoastron of the migrating planet.

5.5. Opening angle

From the comparison of Fig. 4 and 5, we can conclude that, in this configuration, the production of dust takes place between $3 \cdot 10^7$ and $7 \cdot 10^7$ years when the inclination of the parent bodies are still low, but already larger than the initial inclination ($< 2^\circ$). Here, the opening angle of the produced disk must be around 3 or 4 degrees.
This angle is smaller than the 7 degrees observed in the β Pictoris case. However, we must remember that we have taken only one planet, the ascending node of its orbit is then constant. But in a more realistic case with several giant planets, the precession of the ascending nodes can produce a significant increase of the parent bodies inclination. It is reasonable to believe that the process which gives the large inclination of Pluto or Kuiper belt objects in Malhotra’s simulations with several planets (Malhotra 1995) can give a large inclination of the parent bodies in the β Pictoris disk. This migrating and resonance trapping process can give large increase in the inclinations up to several degrees (bottom panel of Fig. 9), and consequently give a large opening angle of the associated dust disk.

5.6. Stability of trapping

We have checked that the bodies trapped in the far resonance 1:4 with the parameters given above are steadily trapped in spite of some perturbations expected to be there.

For example, the motion of the perturbing planet resulting from the scattering of large planetesimals could cause a shift of the resonance and a disruption of the resonance trapping. However, simulations show that the perturbation has a negligible effect as soon as Δv/v ≲ 10⁻³.

The resonance stability to non-gravitational forces acting on evaporating bodies has also been checked. For non-gravitational forces in the form \( \mathbf{F} = -A_1 \mathbf{F}_g \) where \( \mathbf{F}_g \) is the central star gravitation and \( A_1 \lesssim 500 \cdot 10^{-5} \) (Sekanina 1981), no consequence on the resonance trapping has been observed.

Perturbation from other planets will be evaluated in a forthcoming paper. Some effects can be expected like the increase of the bodies inclination. Preliminary results show that the effect on the stability of the trapping and the statistics of the number of bodies which are trapped is negligible.

5.7. Conclusion

The consequences of the Fernández’s scenario on the small bodies of our own Solar System are limited to dynamical phenomena like the orbits of Pluto or the structure of the Kuiper belt as proposed by Malhotra, because the distance of Neptune is large in comparison to the evaporation limit of the common volatiles. The situation can be different around brighter stars like β Pictoris or stars surrounded by smaller planetary systems.

We have shown that the formation and migration of one outer planet in the Fernández’s scheme can explain the observed properties of the dust disk around β Pictoris. Indeed, it has been shown that planetesimals can be trapped in the resonances with the planet in such a way that it is likely that they produce dust and gas by evaporation.

If this model is confirmed to be successful and the evolved disks are the signatures of current dynamic evolution around main sequence stars, future observations of circumstellar disks will give information on the structure and the time scales of the formation of the outer planets in planetary systems.

6. Conclusion

Collisions and evaporation are the two main processes believed to be able to supply disks like the β Pictoris one. These two processes are not exclusive: both can occur at different places or with different time-scales.

However, the β Pictoris disk is more likely produced by the evaporation process. The CO and C i gas detected with HST definitely shows that evaporation takes place around β Pictoris, even if its consequence on dust replenishment in comparison to the collisional production is still a matter of debate. The dust spatial distribution with the slope of the power law, and the central hole can be explained by the characteristic distances of evaporation. Finally, the asymmetry at large distances can easily be explained in evaporating scenarios because the parent bodies are maintained close to the star where planets’ influences are important. The asymmetry is then simply a consequence of the non-axisymmetry of the perturbation by planet(s) on eccentric orbits.

We have presented some possible origins of the OEBs. The direct consequence of some mechanisms to drive the parent bodies inside the evaporation zone is that the β Pictoris phenomenon can be transient, with periods of large activity.

We have shown the possibility that bodies trapped in resonances with a migrating planet can evaporate. This allows to explain the asymmetry observed in the β Pictoris disk; the needed large number of CO evaporating bodies is realistic and explained by a transient evaporation during a short period.

From another point of view, if the migration of the outer planets took place in the Solar System and had consequences on small bodies like Pluto or the Kuiper belt objects, why not around other stars? This is in fact a simple consequence of the presence of a forming planet inside a disk of residual planetesimals: the interaction between the planet and these planetesimals can eject some planetesimals on eccentric orbits (FEBs?) and this ejection causes a back-reaction on the planet which migrates. In details, as shown by Fernández (1982), several planets are needed and the planetesimals are the medium for the momentum exchange between these planets. Here we have explored the new consequence of the migration of a forming planet. The small bodies can be trapped in resonances, and then, because their eccentricities increase, they can enter inside evaporation zone and become parent bodies of β Pictoris-like disks. In short, as a direct consequence of the formation of outer planets in the Fernández’s scheme,
evaporation of Kuiper belt-like objects around stars can be expected to be common. This allows us to look at the circumstellar disks around main sequence stars as a possible signature of outer planet formation.

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Appendix A: The carbon bearing gas: a clue to evaporation

In this Appendix we evaluate the total mass of CO present around \( \beta \) Pictoris (\( M_{\text{CO}} \)) and the corresponding supplying rate (\( \dot{M}_{\text{CO}} \)). We will see that this can give an independent clue to the presence of Orbiting-Evaporating-Bodies.

A.1. The gas around \( \beta \) Pictoris

The gaseous part of the \( \beta \) Pictoris disk is detected through the gaseous absorptions superposed on the stellar spectrum. These absorptions are now classified in four different groups (see review by Vidal-Madjar et al. 1998): the interstellar absorption from the local cloud at 10 km s\(^{-1}\); a stable component at the stellar velocity (21 km s\(^{-1}\)) which is considered as the gaseous counterpart of the dust disk (nevertheless the link between the stable gas and the dust disk is still not established and may even not exist); slow and rapid variable absorptions, mainly redshifted, and well-explained by the so-called Falling-Evaporating-Bodies (FEBs) which are star-grazing evaporating comets. It is thus largely accepted that kilometer-size bodies orbit about \( \beta \) Pictoris and some are subject to evaporation (see also Lecavelier des Etangs et al. 1997).

In the FEB scenario, the link between gas and dust is faint, there is no direct connection between the presence of dust and infalling material. The dust produced simultaneously with the gas by Falling-Evaporating-Bodies on eccentric orbits must be quickly expelled by radiation pressure on hyperbolic orbits. It is likely that we are now observing two different phenomena which both take place in the \( \beta \) Pictoris system: presence of dust as around the prototypical star Vega, and presence of falling gas.

A.2. A needed source of CO and C\( \text{i} \)

An important characteristic of the \( \beta \) Pictoris gaseous disk is the presence of cold CO and C\( \text{i} \) (Deleuil et al 1993, Vidal-Madjar et al. 1994). Although the CO and C\( \text{i} \) absorption lines are observed at the stellar velocity as the stable component detected by the absorption lines of single ionized ions (Ca \( \text{II} \), Fe \( \text{II} \), Mg \( \text{II} \), etc...), there is evidence that CO and C\( \text{i} \) have a special status:

- CO is cold with a typical temperature of less than 30 K which corresponds to the temperature of CO-evaporation; for instance, with an albedo of 0.5 this temperature corresponds to an evaporating body located between 100 and 200 AU (Lecavelier des Etangs 1996). This temperature is also consistent with the observed \(^{12}\text{CO}/^{13}\text{CO} \) ratio of \( R = 20 \pm 5 \) (Jolly et al. 1998). This temperature is obviously very different from the temperature of the falling ionized gas: e.g., the Ca \( \text{II} \) triplet lines show that this gas reaches locally very high temperature (\( T_e > 15 \, 000 \, \text{K} \), Mouillet & Lagrange 1995).

- In contrary to the single ionized ions or Na \( \text{i} \), also observed in the diffuse interstellar medium, CO and C\( \text{i} \) are destroyed by UV interstellar photons and have lifetime shorter than the star age (\( t_{\text{CO}} \sim t_{\text{C\( \text{i} \)}} \sim 200 \, \text{years} \)). A permanent replenishment mechanism must exist.

- With the two arguments given above, the supplying rate of CO (and consequently, C\( \text{i} \)) can be roughly estimated and constrained. For this estimate, one must assume a cloud geometry which gives the connection between the observed column density and the total CO mass. Assuming a disk geometry with an opening angle similar to the dust disk (\( \theta = 7\pm3 \, \text{degrees} \)), and a characteristic distance given by the CO temperature (\( r_0 = 150\pm50 \, \text{AU} \)), we get a mass of CO

\[
M_{\text{CO}} \approx 4\pi \mu_{\text{CO}} N_{\text{CO}} r_0^2 \approx 7 \times 10^{20} \, \text{kg} \tag{A.1}
\]

within a factor of 5, where \( \mu_{\text{CO}} \) is the molecular weight and \( N_{\text{CO}} = 2 \pm 1 \times 10^{15} \, \text{cm}^{-2} \) is the column density of CO.

Then the known photodissociation rate of CO, \( \tau_{\text{CO}} = 2 \times 10^{-19} \, \text{s}^{-1} \) (Van Dishoeck & Black, 1988) gives a relation between the total mass and supplying rate. We obtain

\[
\dot{M}_{\text{CO}} = M_{\text{CO}} \tau_{\text{CO}} \approx 10^{11} \, \text{kg} \, \text{s}^{-1} \tag{A.2}
\]

A.3. Evaporation

We see that CO and C\( \text{i} \) probably have a different origin than the other observed species and anyway need a permanent replenishment mechanism. The most obvious mechanism is certainly the evaporation of cometary-like bodies. In that case, CO is ejected from the evaporating body, C\( \text{i} \) is then produced through the CO dissociation (Vidal-Madjar et al. 1994, Jolly et al. 1998). This evaporation can take place in two different ways:

- In Solar System, frosted bodies like comets are ejected on very eccentric orbits inside the evaporation zone. The evaporation is thus very rapid, these comets become exhausted in a few hundred revolutions. A lot of volatiles are evaporating: CO, but also CO\( \text{2} \) and H\( \text{2} \)O.

- A second mechanism can also provide evaporation of frosted volatiles: the parent bodies can slowly evaporate if their orbit progressively enters the evaporation limit.
In fact, the evaporation rate is very dependent on the distance to the star ($\sim r^{-20}$, Fig. 3 of LVF), and the distance below which the gas evaporates can thus be considered as very sharp. The consequence of such evaporation of bodies still on quasi-circular orbits is that the dust can remain on elliptical orbit around the star. For typical grain size distribution and assuming that the largest grains are larger than 10$\mu$m, one can estimate that less than 50% of the mass is ejected on a hyperbolic orbit in the dust tail, the remaining is distributed on a large disk structure (LVF). Chiron is subject to such evaporation (Luu & Jewitt 1990). However this cannot happen frequently in the Solar System because the evaporation of the common volatiles takes place inside the planetary system. There, massive planets are responsible for strong gravitational perturbations and put the evaporating bodies on very eccentric orbit; these are then observed as classical comets. This is also why Chiron has a chaotic orbit and will not remain a slow evaporating body for a long time (Scholl 1979).

On the contrary, this slow evaporation can occur in an extra-solar planetary system if the evaporation limit is outside the massive planets orbits. For example, this could be the case if a planetary system similar to the Solar System was present around a star brighter than the Sun.

In LVF, we have estimated the total mass of dust associated with the observed CO around $\beta$ Pictoris, if it is produced in such a slow evaporation of orbiting bodies. With reasonable parameters the mass is found to be consistent with the total mass of observed dust (see also Sect. 3); this provide an independent evidence that the $\beta$ Pictoris dust disk can be supplied by Orbiting-Evaporating-Bodies.

References

Artyomowicz P., 1988, ApJL 335, L79
Artyomowicz P., 1997, Annu. Rev. Earth Planet. Sci. 25, 175
Artyomowicz P., Burrows C., Paresce F., 1989, ApJ 337, 494
Artyomowicz P., Paresce F., Burrows C., 1990, Adv. Space Res. 10, (3)81
Aumann H.H., Gillett F.C., Beichman C.A., et al., 1984, ApJ 278, L23
Backman D.E., Gillett F.C., Witteborn F.C., 1992, ApJ 385, 670
Backman D.E., Paresce F., 1993, in Protostars and Planets III, Eds. E.H. Levy, J.I. Lunine & M.S. Matthews (Tucson: Univ. Arizona Press), pp 1253
Backman D.E., Dasgupta A., Stencel R.E., 1995, ApJ 450, L35
Biver N., Rauer H., Despois D., et al., 1996, Nature 380, 137
Burns J., Lamy P., Soter S., 1979, Icarus 40, 1
Cochrane W.D., Hatzes A.P., Butler R.P., Marcy G.W., 1997, ApJ 483, 457
Crifo F., Vidal-Madjar A., Lellement R., Ferlet R., Gerbaldi M., 1997, A&A 320, I29
Deleuil M., Gry C., Lagrange-Henri A.M., et al., 1993, A&A 267, 187
Duncan M.J., Levinson H.F., 1997, Science 276, 1670
Elliot J.I., Olkin C.B., Dunham E.W., et al., 1995, Nature 373, 46
Fajardo-Acosta S.B., Knacke R.F., 1995, A&A 295, 767
Fajardo-Acosta S.B., Telesco C.M., Knacke R.F., 1993, ApJ 417, L33
Fernández J.A., 1982, A.J. 87, 1318
Fernández J.A., Ip W.H., 1996, Planet. Space Sci. 44, 431
Golimowski D.A., Durrrance S.T., Clampin M., 1993, ApJ 411, L41
Habing H.J., Bouchet P., Dominik C., et al., 1996, A&A 315, 233
Jewitt D., Senay M., Matthews H.E., 1996, Science 271, 1110
Jolly S., McPhate J.B., Lecavelier des Etangs A., et al., 1998, A&A 329, 1028
Kalas P., Jewitt D., 1995, AJ 110, 794
Knacke R.F., Fajardo-Acosta S.B., Telesco C.M., et al., 1993, ApJ 418, 440
Lagage P.O., Pantin E., 1994, Nature 369, 628
Lecavelier Des Etangs A., 1996, Thèse de l'Université Paris VII
Lecavelier Des Etangs A., Perrin G., Ferlet R., et al., 1993, A&A 274, 877
Lecavelier des Etangs A., Vidal-Madjar A., Ferlet R., 1996, A&A 307, 542, (LVF)
Lecavelier Des Etangs A., Vidal-Madjar A., Burki G., et al., 1997, A&A 328, 311
Lissauer J.J., 1993, Ann. Rev. Astron. Astrophys. 31, 129
Lissauer J.J., 1987, Icarus 69, 249
Luu J.X., Jewitt D.C., 1990, AJ 100, 913
Malhotra R., 1993, Nature 365, 819
Malhotra R., 1995, AJ 110, 420
Mayor M., Queloz D., 1995, Nature 378, 355
Mazeh T., Krymolowski Y., Rosenfeld G., 1997, ApJ 477, L103
Meech K.J., Buie M.W., Samarasinha N.H., et al., 1997, AJ 113, 844
Morbidelli A., 1997, Icarus 127, 1
Mouillel D., Lagrange A.M., 1995, A&A 297, 175
Mouillel D., Lagrange A.M., Beuzit J.L., Renaud N., 1997a, A&A 324, 1083
Mouillel D., Larwood J.D., Papaloizou J.C.B., Lagrange A.M., 1997b, MNRAS 292, 896
Scholl H., 1979, Icarus 40, 345
Sekanina Z., 1981, in Comets, Ed. L.L. Wilkening, (Tucson: Univ. Arizona Press), p 251
Sekanina Z., 1987, A&A 187, 789
Skinner C.J., Barlow M.J., Justtanont K., 1992, MNRAS 255, 31P
Smith B.A., Terrile R.J., 1984, Sci 226, 1421
Smith B.A., Terrile R.J., 1987, BAAS 19, 829
Sylvester R.J., Skinner C.J., Barlow M.J., Mannings V., 1996, MNRAS 279, 915
Torbett M.V., Smoluchowski R., 1990, Nat. 345, 49
Van Dishoeck E.F., Black J.H., 1988, ApJ 334, 771
Vidal-Madjar A., Lagrange-Henri A.M., Feldman P.D., et al., 1994, A&A 290, 245
Vidal-Madjar A., Lecavelier des Etangs A., Ferlet R., 1998, Planet. Space Sci., in press
Weidenschilling S.J., Marzari F., 1997, Nature 384, 619
Weissman P.R., 1984, Science 224, 987
Zuckerman B., Becklin E.E., 1993, ApJ 414, 793