CIRCUMSTELLAR DISKS AND OUTER PLANET FORMATION

A. LECAVELIER DES ETANGS
Institut d’Astrophysique de Paris
98 Blvd Arago, F-75014 Paris, France

Abstract.

The dust disk around $\beta$ Pictoris must be produced by collision or by evaporation of orbiting Kuiper belt-like objects. Here we present the Orbi-
ting-Evaporating-Bodies (OEB) scenario in which the disk is a gigantic multi-cometary tail supplied by slowly evaporating bodies like Chiron. 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. 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 (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.

1. Introduction

The infrared excess Vega-like stars and their circumstellar dusty environment have been discovered by IRAS in the 80’s (Aumann et al. 1984). 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 can be summarized as follows (see Lecavelier des Etangs et al., 1996, hereafter LVF):
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 (Golimowski et al. 1993). Second, the disk has an inner hole with a central part relatively clear of dust (Lagage & Pantin 1994). In the third dimension, the disk is a “wedge” disk: the thickness increases with radius (Backman & Paresce 1993). More surprisingly, the disk is not symmetric with one branch brighter than the other (see details in Kalas & Jewitt, 1995). Finally, the inner part of the disk (∼ 40 AU) seems to be warped. This warp has been well-explained by Mouillet et al. (1997) 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), we present its consequences on the explanation for the presence of CO (Sect. 3) and the asymmetry (Sect. 4). Then, we will see that the βPictoris disk can be a natural consequence of the formation of Neptune-like outer planets (Sect. 5).

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. 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: $F(r) \propto r^{-\alpha}$, with $\alpha \sim 5$ (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 zero order model is steeper than the observed slope of the power law in the β Pictoris disk ($\alpha \sim 4$, Kalas & Jewitt 1995).
To explain this distribution, it is possible that the dust is produced by collisions of Kuiper belt-like objects spread in a wide range of distances. But, an alternate solution is also possible in keeping the assumption that the parent bodies remain in a narrow ring close to the star. In that case, a large quantity of small particles is needed, because these particles have larger apostron and can explain the less steep slope in the power law. These small particles can typically be produced by the evaporation of parent bodies of size $\sim 10\text{km}$ and located at large distances. 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 bodies 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).

Several arguments are in favor of this scenario in the case of the $\beta$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. Of course the CO/dust ratio is one of the arguments which is in favour of the OEB scenario (see Sect. 3). Finally, the connection between the inner radius of the disk and evaporation limit is a direct consequence of this scenario because the periastron distances of the particles are similar to the periastron of the parent bodies. Any hypothetical planet at this limit is no more needed to explain the presence of the inner void in the disk.

3. The Carbon Bearing Gas: a Clue to Evaporation

3.1. A Needed Source of CO

An important characteristic of the $\beta$ Pictoris gaseous disk is the presence of cold CO and C i (Vidal-Madjar et al. 1994). 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. CO and C i are destroyed by UV interstellar photons and have lifetimes shorter than the star age ($t_{\text{CO}} \sim t_{\text{CI}} \sim 200$ years). A permanent replenishment mechanism must exist. To estimate the supplying rate of CO, 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 ($\theta = 7$ degrees), and a characteristic distance given by the CO temperature ($r_0 = 150$ AU), we get a mass of CO: $M_{\text{CO}} \approx 4\pi \theta \mu_{\text{CO}} N_{\text{CO}} r_0^2 \approx 7 \times 10^{20}\text{kg}$, where $\mu_{\text{CO}}$ is the molecular weight and $N_{\text{CO}} = 2 \times 10^{15}$ cm$^{-2}$ is the column density of CO. Then, the known photodissociation rate of CO, $\tau_{\text{CO}} = 2 \cdot 10^{-10}\text{s}^{-1}$ (Van Dishoeck & Black,
(1988) gives a relation between the total CO mass and the corresponding supplying rate. We obtain $\dot{M}_{\text{CO}} = M_{\text{CO}}\tau_{\text{CO}} \approx 10^{11}\text{kg s}^{-1}$.

We can also estimate the needed supplying rate of dust $\dot{M}_{d} = M_{d}/t_{d} \approx 10^{11}\text{kg s}^{-1}$, where $M_{d}$ is the mass of the dust disk ($M_{d} \sim 10^{23}\text{kg}$), $t_{d}$ is the dust life-time ($t_{d} \approx 10^{4}\text{yr}$). It is very interesting to see that the dust/CO supplying rate is consequently $\dot{M}_{d}/\dot{M}_{\text{CO}} \approx 1$. This very similar to the ratio in the material supplied by evaporation in the solar system. This provide an independent evidence that the $\beta$ Pictoris dust disk can be supplied by Orbiting-Evaporating-Bodies.

We can now estimate the number of bodies producing this CO. If we take an evaporation rate of CO per body $Z_{\text{body}} \sim 5 \times 10^{28}\text{body}^{-1}\text{s}^{-1}$, $N_{\text{CO}}$ the number of bodies now evaporating CO around $\beta$ Pictoris must be $N_{\text{CO}} = (M_{\text{CO}}\tau_{\text{CO}})/(Z_{\text{body}}\mu_{\text{CO}}) \approx 6 \cdot 10^{7}$ bodies. This number is extremely large but unavoidable because CO is observed. 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. Anyway, the mass of parent bodies required by the evaporation process (about one Earth mass, provided that some process is able to start its evaporation) is well below the mass needed to supply the $\beta$ Pictoris disk only by collision ($30\text{ Earth}$, Backman et al. 1995).

3.2. $\beta$ PICTORIS A TRANSIENT PHENOMENON?

It could be difficult to imagine that $\sim 10^{8}$ bodies have always been active for $\sim 10^{8}$ years. $M_{\text{CO}} \times 10^{8}\text{years} \times \tau_{\text{CO}} = 20M_{\text{Earth}}$ of CO should 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 $\beta$ Pictoris is very young or that it is a transient phenomenon. There is in fact no reason to believe that the $\beta$ 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 $\beta$ 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 Asymmetry Problem

In contrast to a production by a set of collisional bodies at very large distances where planets have no influence, if the dust is produced by a narrow ring of orbiting evaporating bodies, these bodies must be close to the star where the planetary perturbations can be important. In this case,
Figure 1. Plot of the spatial distribution of the periastron of a set of bodies located between 70 and 90 AU and perturbed by a planet on eccentric orbit ($M_p = 3 \cdot 10^{-4} M_\odot$, $e_p = 0.05$, $a_p = 30$ AU). We see that the density of bodies with periastron in the direction of the planet periastron (black dot) is very large. Moreover the periastron distances are also smaller. For these two reasons, the dust production by evaporation must be larger in this direction. If these bodies evaporate, they produce a dust disk which must be asymmetric.

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 periastron 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 perturbing planet periastron could be more dense (an example of such a situation is given in Fig 1).
5. Resonances with a Migrating Planet

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 its periastron distance then decreases below this limit.

5.1. THE FORMATION OF URANUS AND NEPTUNE

To solve the problem of time scales for the formation of the outer planet of the Solar System, Fernández (1982) suggested 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. This model successfully explains the formation of the two outer planets of the Solar System, in short time scale ($2 \times 10^8$ to $3 \times 10^8$ years), their mass and their actual position (Fernández & Ip 1996).

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 its large eccentricity and inclination, and its resonance with Neptune. In short, Pluto was trapped in the orbital commensurability moving outward during the expansion phase of Neptune's orbit. The outward migration of Neptune can also explain the fact that numerous Kuiper belt objects are observed in Pluto-like orbit in 2:3 resonance with Neptune (Malhotra 1995).

5.2. PLANET MIGRATION AND PERTURBATION ON PARENT BODIES.

With this in mind, it is interesting to evaluate the possible link between the migration of outer planets and the β Pictoris-like circumstellar disks for which we know that the age is similar to the time scale of formation of these planets ($10^8$ years is about the age of β Pictoris and α PsA). 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. Of course, at least a second inner planet must be there. Here, we consider only the principal outer perturbing planet which is supposed to migrate because
Figure 2. Left panel. Plot of the orbital parameters semi-major axis ($a$), eccentricity ($e$), periastron ($q$) and inclination ($i$) of 19 bodies trapped in the 1:4 resonances with a migrating planet. We see that although the semi-major axis of the bodies increase, their periastron decrease. These bodies can start to produce dust by evaporation.

Right panel. Plot of the dust production as a function of time for evaporating bodies trapped in 1:4 resonance with a migrating planet. This is the dust production for grains larger than 2$\mu$m, because smaller grains are supposed to be quickly expelled by the radiation pressure. The production of dust starts when the periastron distance of the parent bodies is small enough for the CO production rate to allow ejection of grains larger than 2$\mu$m. Then, it stops when the parent bodies are exhausted and have no more volatile. Consequently, the dust production is transient and is large only when the bodies trapped in the resonances are entering in the evaporation limit. The production rate is also not axisymmetric. As in Sect. 4, we see that the production is larger in the direction of the periastron of the perturbing planet (long dashed) than in the opposite direction (short dashed).

The right bottom panel gives the corresponding maximal size of grains ejected from the bodies by the evaporating gas. Because the periastrons are still larger than 100 AU, the evaporation produces only small particles. In this simulation, the maximal particle size is around 4$\mu$m as expected to explain the slope $\alpha \sim 4$ observed in the $\beta$ Pictoris case.

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.

In fact, if the migrating planet is moving inward, the planetesimals are not 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 outer planet is moving outward, as found in the models of Fernández & Ip (1996), 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. This can start the evaporation of the trapped bodies.

We have tested several configurations of outward migration and have
evaluated the effect on planetesimals in the zones swept by first order resonances. The 1:2 and 1:3 resonances does not allow to explain the observed characteristics of the β Pictoris disk. The 1:4 resonance give the most interesting results (Fig. 2). The trapping has been found to be efficient if the mass of the planet is $M_p \gtrsim 0.5M_J$, where $M_J$ is the mass of Jupiter, and if the migration rate is $\tau > \gtrsim 5 \cdot 10^7$ years. With these conditions, the periastron of trapped bodies significantly decreased. A significant increase of the inclination has also been observed after few $\tau$ as well as a large asymmetry in the distribution of the periastrons longitude. The 1:5 resonance is efficient in trapping only if the parameters of the migrating planet are extreme with $M_p \gtrsim M_J$, $e_p \gtrsim 0.1$ and $\tau > \gtrsim 5 \cdot 10^7$ years.

5.3. ASYMMETRY AND OPENING ANGLE

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. For example, the Fig. 2 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 apoaprastron of the migrating planet.

From Fig. 2, we also conclude that the production of dust can take place with the inclination of the parent bodies larger than the initial inclination, up to several degrees. Moreover, with several giant planets, the precession of the ascending nodes can produce an additional increase of the parent bodies inclination. In all cases, this migrating and resonance trapping process gives a large increase in the inclinations and consequently a large opening angle of the associated dust disk.

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. 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 shown the possibility that bodies trapped in resonances with
a migrating planet can evaporate. The large number of CO evaporating
bodies is 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, 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. Here we have explored a new consequence
of this migration of a forming planet. Some planetesimals can be trapped in
resonances, enter inside evaporation zone and finally 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 bright 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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