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Scattering of Planetesimals from Young Planetary Disks: Application to the β Pictoris System

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Abstract. Transient redshifted events monitored in the spectrum of β Pictoris have been interpreted as resulting from the evaporation of numerous comet-like bodies in the vicinity of this star. The dynamical origin for this phenomenon is attributed to mean-motion resonances (4:1 and 3:1) with a Jovian-like planet. Numerical simulations of this phenomenon are able to correctly reproduce the dynamical characteristics of the star-grazers observed. The numerical study allows to estimate the density of the planetesimal disk from which the bodies are supposed to originate, i.e. $\sim$ a few 10^8 bodies per AU. A key issue with this model is the refilling of the resonances, as without refilling they should be cleared within a few 10^5 yr and the observed phenomenon should stop. Collisions among planetesimals are a plausible mechanism. Collisional simulations show that collisions are able to sustain the observed phenomenon over much more than 10^6 yr, provided the population of the disk is high enough. The mass density of this population is estimated to a few tens of Earth masses per AU, which is only marginally realistic. However, the mass estimate is very poorly constrained.

1. β Pictoris

The $10^7 - 10^8$ yr old star β Pictoris (β Pic) is surrounded by a dusty and gaseous disk which has been intensively studied for now 16 years. This system is still regarded today as the best example of a possible extra-solar planetary system in its early dynamical evolutionary phase (see reviews by Artymowicz 1997; Vidal-Madjar et al. 1998). It is known today that the dusty particles viewed on the disk images are not a remnant of any primordial disk, but rather second generation material continuously replenished from inside the disk probably by planetesimals. Moreover, the presence of planets within the disk is also strongly suspected to explain the various asymmetries observed in the shape of the dusty disk (Kalas and Jewitt 1995; Mouillet et al. 1997).

2. Falling Evaporating Bodies

The study of the gaseous counterpart of the disk also provides indication for the presence of planetesimals orbiting β Pic. The survey of various spectral lines of metallic species (Ca II, Mg II, Fe II, etc...) towards this star revealed that transient absorption features, usually redshifted, frequently appear or disappear, within one day or even less (Vidal-Madjar et al. 1994; Lagrange et al. 1996). These repeated spectral events have been successfully modeled as the signature of the evaporation of kilometer-sized bodies crossing the line of sight in the vicinity of the star, on star-grazing orbits (Beust et al. 1996, 1998). This scenario is known today as the Falling Evaporating Bodies (hereafter FEB) scenario.

The various types of spectral events have been classified in three different sets (see Beust et al. 1998), depending on their typical depths, redshift velocities, apparition frequencies, and variations time-scales. In the frame of the FEB scenario, these various features are naturally explained by bodies that cross the line of sight at different distances to the star, from the stellar surface, up to the evaporation limit of refractory material around β Pic (~ 0.4 AU).

3. The dynamical origin of FEBs

A key issue concerning the FEB scenario was the identification of a triggering dynamical mechanism capable to bring numerous bodies on star-grazing orbits, out of a Keplerian rotating disk on quasi-circular orbits. Various mechanisms were proposed, all of them involving the gravitational perturbations by at least one planet, preferably massive. The most convincing one was proposed by Beust & Morbidelli (1996): *Mean-motion resonances* (4:1 and 3:1) with a massive planet orbiting the star on a moderately eccentric orbit ($0.05 \lesssim e' \lesssim 0.1$), can bring bodies up to virtually $e \simeq 1$ eccentricity within $\sim 10^4$ planetary orbits.

The 4:1 resonance appears to be by far the most powerful resonance for FEB generation, since nearly every body trapped in it reaches $e \simeq 1$. This scenario is numerically investigated in Beust and Morbidelli (2000), assuming a Jovian-like planet orbiting the star at 10 AU. Contrary to other mechanisms, this model generates a non-axisymmetric FEB infall, i.e., the distribution of the longitudes of periastra of the FEBs is not uniform. Beust and Morbidelli (2000) show indeed that assuming a convenient value for the longitude of periastron of the planet with respect to the line of sight ($\varpi' \simeq -70°$), the observed velocity distribution of the various spectral events can be fairly well reproduced.

4. The refilling issue

An important problem with this model is the duration of the FEB episode. Indeed, 10^5 yr is the characteristic time for a given body to become FEB. After many periastron passages, the body is fully evaporated. As a result of this process, the population of the resonance is cleared out of FEB candidates within a similar time-scale, i.e. 10^5 to 2×10^5 yr. This clearly showed up in the simulations.

The problem is that this time-scale is only a small fraction of the estimated age the system (10^7 – 10^8 yr). The resonance should be empty today and the

FEB activity should have ceased a long time ago. If it is still at work today, some mechanism is required to replenish the resonance with new bodies.

In a first attempt, Beust & Morbidelli (2000) made a simple analytical study of the refilling process. Based on the numerical simulations, they estimated the population density $N_{\rm in}$ of FEB progenitors in the 4:1 resonance to $\sim 10^8$ bodies per AU. Basically, two independent refilling mechanisms may be invoked: First, collisions among planetesimals may refill the resonance from bodies adjacent to it; second, a planetary migration (possibly due to planetesimal scattering), inducing a resonance migration, may help new bodies enter the resonance.

The efficiency of the planetary migration model depends critically on the migration velocity. The migration velocities typical for planetesimal scattering are too small to sustain the present FEB activity. Higher migration velocities can, but they are typical for migration by tidal disk-planet interactions which are characteristic for younger and denser disks than β Pic.

Conversely, collisions are a plausible refilling mechanism. Assuming simple collisional equilibrium between the resonant and the regions adjacent to it, it is possible to derive the population density $N_{\rm out}$ *outside* the resonance that is necessary to maintain the population of the resonance $N_{\rm in}$ despite planetesimal consumption by the FEB phenomenon. We derive $N_{\rm out} \simeq 5 \times 10^8$ bodies per AU.

The last step is then to convert this population estimate into a disk mass estimate. We must assume a size distribution, for example a classical $r^{-3.5}$ size distribution. The mass estimate also depends critically on the minimum size we assume for our population, i.e., the size $R_{\rm min}$ of the smallest body that does not evaporate too quickly and actually generates observable events. Beust & Morbidelli (2000) derive $R_{\rm min} \simeq 15\,{\rm km}$. With this value, a mass density of $\sim 20 - 30\,M_\oplus$ per AU is derived. This is high, but still marginally compatible with the mass density estimates in the primordial asteroid belt by Weidenschilling (1977). However, the mass density scales as $R_{\rm min}^3$. As $R_{\rm min}$ is accurate up to a factor 2 or 3 only, the mass estimate turns out to be poorly constrained.

5. The 3:1 resonance

An alternative issue is to consider the 3:1 resonance as a source for FEBs. The 4:1 resonance is more powerful than the 3:1 on a given population of bodies, but the 3:1 is wider in semi-major axis, so that it concerns a priori more particles than the 4:1. Thus, it cannot be neglected. This question is investigated in Thébault & Beust (2001). In this work, we show that this depends critically on the eccentricity of the perturbing planet e'. For $e' \simeq 0.07$ (the value assumed in Beust & Morbidelli 2000), the 4:1 still dominates the flux, but for $e' = 0.1$ the situation is reversed.

In the latter case, a more refined study made by Thébault and Beust (2001) shows that refilling of the resonance by collisions is actually able to sustain a constant and significant FEB activity over more than 10^6 yr (and in fact probably more; the only limit is the integration time). Applying to this constant level the same analysis as above, we derive a disk mass estimate $\sim 10\,M_\oplus$ per AU which is more acceptable.

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6. Conclusion

The FEB scenario reproduces very well the variable spectral events observed towards β Pic in all their characteristics. It implies the presence of at least one giant planet (Jupiter-sized), orbiting the star between ~ 5 and ~ 25 AU. This is compatible with the constraints deduced from disk asymmetries modeling.

The FEBs themselves originate from the 3:1 and 4:1 mean-motion resonances with that planet. The collisions among the planetesimal population are able to refill the resonance and thus sustain the FEB activity over the age of the system. The implied mass density of the disk is high but still realistic.

Finally, we would like to compare this picture to the one that is thought to have applied in the primordial asteroid belt in the Solar System. The mechanism that gave birth to the Kirkwood gaps is basically the same as the one we invoked as the origin of the FEB phenomenon towards β Pic, and it is supposed to have been at work at an age comparable to the present age of β Pic. Of course in the Solar System, a lot of detailed work has been done showing the very important additional role of secular resonances to mean-motion ones in eccentricity pumping (Morbidelli & Moons 1993; Moons & Morbidelli 1995). But we cannot exclude this more refined picture to apply to the β Pic case. We just simply cannot constrain it more precisely.

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