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HIGH LATITUDE GAS IN THE β Pictoris SYSTEM – A POSSIBLE ORIGIN RELATED TO FALLING EVAPORATING BODIES

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Abstract. Transient spectral events towards the southern star Beta pictoris have been attributed to the sublimation of transiting star-grazers planetesimals (Falling Evaporating Bodies, or FEBs). The FEBs are supposed to originate from mean-motion resonances with a massive planet. In 2004, spectral emission in Ca II and Fe II was detected at 100 AU away from the star, but above the midplane of the disk (Brandeker et al. 2004). We show that the presence of off-plane ions can be explained in the frame of the FEB scenario, as due to inclination oscillations caused by the resonance (Beust & Valiron 2007) in the high eccentricity regime. The ions released by the FEBS in this regime keep track of their inclination and start evolving out of the plane. Their are stopped at 100 AU from the star probably by some dense medium.

1 Introduction

The dusty and gaseous disk surrounding the young main-sequence star β Pictoris has been the subject of intense investigation since its discovery (Smith & Terrile 1984). Its debris disk is an example of a probable young planetary system. The gaseous counterpart of the dust disk was detected in absorption in the stellar spectrum (Hobbs et al. 1985), and has been regularly observed since that time. Observations of many metallic species such as Na I, Ca II, Fe II... have been reported (Vidal-Madjar et al. 1994).

Doppler-shifted, highly time-variable components are regularly observed in the spectral lines of many elements (Ferlet et al. 1987, Lagrange et al. 1998, Petterson & Tobin 1999) These transient spectral events have been successfully modelled as resulting from the sublimation of numerous star-grazing planetesimals (several hundred per year) in the immediate vicinity of the star (see Beust et al. 1996, 1998 an refs. therein). This scenario has been termed the *Falling Evaporating Bodies* scenario (FEBs).

From a dynamical point of view, the origin of these numerous star-grazers seem to be related to mean-motion resonances (mainly 4:1 and 3:1) with a Jovian planet orbiting the star on a moderately eccentric orbit ($e' \simeq 0.07$–0.1) (Beust & Morbidelli 1996,2000) An important outcome of this model is that it implies an important reservoir of planetesimals in the disk and the presence of at least one giant planet at ~ 10 AU from the star. This is another argument in favour of the presence of planets in the β Pic disk.

Radiation pressure affects not only dust particles, but also the metallic species seen in absorption with respect to the star. Many of them undergo a radiation force from the star that largely overcomes the stellar gravity (Lagrange et al. 1998). In a recent paper, Brandeker et al. (2004, hereafter B04) report the detection with VLT/UVES of *emission* lines of metals (Fe I, Na I, Ca II) in the β Pic disk, i.e., away from the direction of the star. They report the detection of Na I and Fe I up to more than 300 AU from the star. Na I was resolved earlier by Olofsson et al., but the detection of B04 extends further out.

A particularly puzzling outcome of the B04 observations is the detection of Ca II emission at fairly high latitude above the mid-plane of the disk. Ca II is detected at 77 AU height above and below the mid-plane at 116 AU from the star. This corresponds to an inclination of 33° above the mid-plane. At this distance, Ca II is detected in both branches of the disk and on both sides of the mid-plane, and the emission at 33° inclination largely overcomes that in the mid-plane. Surprisingly, the Fe I and Na I emission do not exhibit such a structuring. It is conversely concentrated in the mid-plane of the disk. However, the Fe I emission is broader

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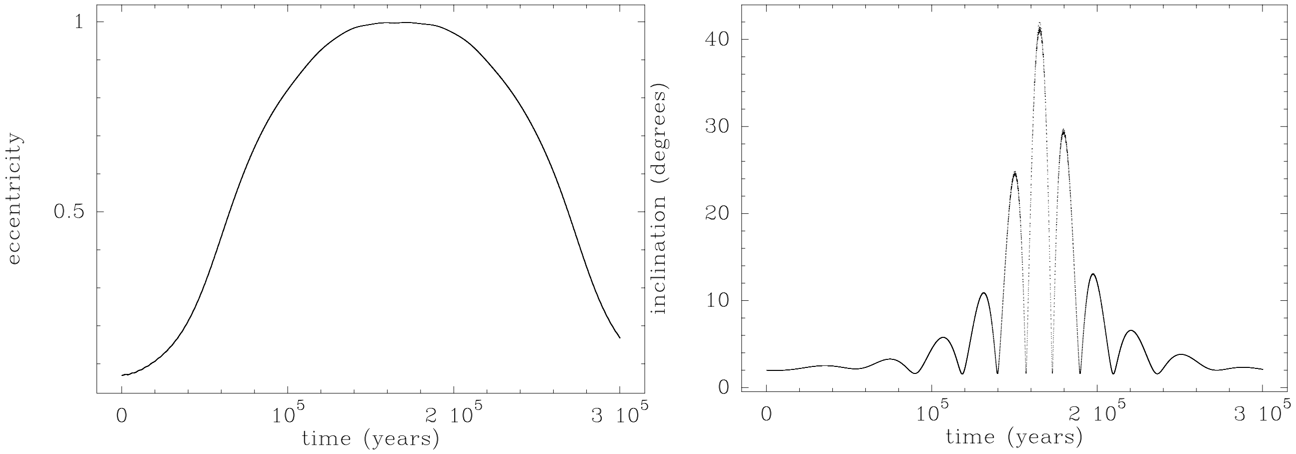

Fig. 1. Temporal evolution of the eccentricity (top) and of the inclination (bottom) of a typical particle trapped in 4:1 resonance with a planet orbiting β Pic at 10 AU with eccentricity $e' = 0.07$. The planet's mass is 1/1000 of that of the star. The initial eccentricity of the particle is 0.05 and its initial inclination is 2°.

than the Na I. At the height above the mid-plane corresponding to the peak emission in the Ca II lines, the Fe I is still detected. The gas shares the same radial velocity as the star within 1 or 2 $\mathrm{km\,s^{-1}}$ at most.

There is no straightforward explanation for the presence of species like Ca II *at such latitudes above the disk, nor for the absence of other species.* The purpose of this paper (see details in Beust & Valiron 2007) is to propose that this gas could constitute material released by the FEBs in the vicinity of the star, first blown away by radiation pressure, and then stopped far away from the star by friction with some gaseous medium, and/or by magnetic interaction. The Ca II and possibly the Fe I reach a significant inclination because the parent bodies (the FEBs) initially orbiting within the plane of the disk undergo inclination oscillations up so several tens of degrees when they reach the star-grazer state. Once released by the FEBs, the ions keep track of that inclination.

2 Falling Evaporating Bodies and high latitude ions

We propose an origin for the high latitude ions observed by B04. Two facts need to be explained: i) Why are there large amounts of gas at 30° above the mid-plane of the disk ? ii) Why is sodium not present in this gas ? We propose that this high latitude gas could be produced by the Falling Evaporating Bodies (FEBs).

The FEBs are star-grazing bodies that fully evaporate in the vicinity of the star. Dynamically speaking, they are planetesimals that have been extracted from the disk orbiting the star and driven to high eccentricity orbits. They enter the FEB regime when their periastron reaches a threshold value (~ 0.4 AU) that allows the refractory material to evaporate.

Beust & Morbidelli (1996) proposed that the FEBs could be generated by mean-motion resonances with at least one major perturbing planet. They showed that the 4:1 and 3:1 resonances are potential sources of FEBs via this mechanism. The only requirement is that the planet's eccentricity e' is not zero. Even small values like $e' \gtrsim 0.05$ are enough, $e' = 0.07$ or 0.1 being typical convenient values. Such eccentricity values are regularly reached by Jupiter due to its secular evolution. This mechanism is close to the one that gave birth to the Kirkwood gaps in the asteroid belt. We are perhaps witnessing in the β Pic system a process similar to what occurred in the Solar System, as it was of comparable age to β Picś current age.

Due to this mean-motion resonance mechanism, a given body, initially trapped in 3:1 or 4:1 mean-motion resonance with a Jupiter-sized planet, may reach the FEB state within $\sim 10^4$ orbital periods of the planet.

The orbits of the FEB progenitors in the mean-motion resonances are assumed to be roughly coplanar with the plane of the disk. In the simulations of Beust & Morbidelli (2000) and Thébault & Beust (2001), the initial inclinations of the particles with respect to the orbit of the perturbing planet were initially chosen as less than 5° and 3° respectively, in order to mimic the typical distribution within a cold planetesimal disk. During their evolution within the resonance, as long as their eccentricity grows, the inclination of the particles remains small, but as they reach the FEB state close to $e \simeq 1$, their inclination is subject to oscillations of larger amplitude, up to several tens of degrees. This is illustrated in Fig. 1, which shows the secular evolution of the eccentricity and of the inclination of a typical particle trapped in 4:1 resonance with a planet orbiting β Pic. The particle starts at eccentricity $e = 0.05$ and evolves towards the FEB state at $e \simeq 1$, and then starts a decrease of its eccentricity. Of course the decrease phase is purely fictitious, as a real FEB would be destroyed by the successive periastron passages at peak eccentricity. The inclination, initially set at 2°, remains small for $\simeq 10^5$ yr and then starts oscillations that brings it far above the initial value, up to 40°. Hence the FEBs may remain within the disk during most of their secular evolution, but finish in the FEB state with inclinations that might bring them significantly out of the disk.

The FEB themselves do not have excursions far out of the plane of the disk, because when their inclination is high, their argument of periastron ω is close to 0° or 180° (Beust & Valiron 2007, hereafter BV07) Conversely, their sublimation byproducts may get out of the disk. The metallic ions released by the FEBs (such as Ca II) start to expand radially around the nucleus Beust et al. (1990, 1996, 1998, see simulations in). Afterwards, they are blown away by the intense radiation pressure they suffer and start a free expansion out of the system.

Dynamically speaking, the ratio of the radiation pressure to stellar gravity is a constant (usually noted β) for a given ion or dust grain. This is equivalent to the view that with radiation pressure, the ion feels the gravity of star as if its mass was multiplied by $1 - \beta$. For Ca II, $\beta > 1$ ($\beta = 35$), so that the ions are strongly repelled by the star. They nevertheless follow a purely Keplerian orbit (hyperbolic repulsive). This orbit is very different to that of the parent body. Both orbits share however the *same orbital plane.* But contrary to the parent body, the orbit of Ca II ions are not confined close to the plane. If they have a high initial inclination, they may evolve far off the plane of the disk as they escape from the system. If some dense medium is present at a given distance to brake them, they may be detected as an extended emission significantly above the plane such as in the B04 observation. Their detection of Ca II at 33° off the mid-plane could then well correspond to ions that have been produced close to the star by FEBs with similar inclination, and that have freely escaped up to 100 AU before being stopped there.

Then, why should this process only concern Ca II and not the other species detected in emission by B04 ? Iron and sodium are byproducts of dust sublimation in FEBs like calcium. Contrary to Ca II, Na I and Fe I are quickly photoionized by the star in the FEB environment. Fe II (like Fe I) still undergoes a radiation pressure that overcomes the stellar gravity (Lagrange et al., 1998), so that iron is expected to behave like calcium. However, unless the electronic density is high, as is the case in the vicinity of the mid-plane disk, iron remains predominantly in the Fe II state whose spectral lines were not searched for by B04. Conversely, Na II does not feel any noticeable radiation pressure, so that once produced, the Na II ions keep following the original orbit of the FEB. They may afterwards diffuse slowly in the mid-plane of the disk, but they are not subject to a quick off-plane ejection like the other species. In this context, we thus expect the gas expelled off-plane by this process to contain calcium and iron with solar relative abundances, but no sodium. This matches our analysis of the emission lines.

The inclination oscillations in the FEB regime depicted in Fig. 1 is not a numerical artefact. The theoretical background of the origin of these inclination oscillations is described in BV07. Phase portraits reveal that during the secular evolution of a resonant particle, the argument of its periastron ω circulates, causing inclination oscillations. The inclination is maximum whenever ω reaches 0 or 180°. At low eccentricity regime the amplitude of this oscillation is small, but in the FEB regime, it can reach several tens of degrees.

This dynamics is a resonant version of the Kozai dynamics, a classical dynamical mechanism for generating star-grazing bodies (Kozai, 1962; Bailey et al., 1992). Finally, in the non-planar case, the dynamics of a resonant particle is characterised by three time-scales : a first, small one related to the libration characteristic for any mean-motion resonance motion; a second, larger one characterising the inclination oscillations; a third, long one describing the secular eccentricity growth from ~ 0 to ~ 1.

3 Stopping the ions

The escaping ions reach the outer part of the disk at $\sim 1000\,\mathrm{km\,s^{-1}}$. As they are obseved at rest with respect to the star, some process is able to efficiently slow at this distance.

This issue was investigated recently by Fernández et al. (2006). They identified three possible braking processes : collisions among ions, collisions with charged ions, and collisions with a neutral gas. Collisions among ions are very efficient only is carbon is overabundant, and collisions with charged grains are only efficient if the grains are mostly carbonaceous (Fernández et al., 2006). Collisions with neutral gas are conversely a good candidate. Fernández et al. (2006) showed that a minimum mass of neutral gas of $\sim 0.03\,\mathrm{M}_\oplus$ is enough to stop the ions. However, due to the high incoming velocity of the Ca II ions, the basic analytic model must be revised.

Neutral species like H I or He I or even H_2 are not subject to any significant radiation pressure from the star (Lagrange et al., 1998); they may thus stay orbiting in a Keplerian way at some distance from the star. The incoming Ca II ions may then collide into this buffer gas and be slowed down to negligible velocity.

When a charged ion approaches a neutral atom at moderate velocity, a dipole is induced on the neutral atom, from which an interaction results between the two particles that is well described by the potential energy

$$V(r) = \frac{1}{4\pi\epsilon_0}\frac{\alpha q^2}{2r^4} \quad , \tag{3.1}$$

where α is the polarizability of the atom, r is the interaction distance, and q is the charge of the ion (McDaniel, 1964). The successive encounters of the ion with the H I medium of density n yield a drag force $\vec{f}$ opposed to velocity (Beust et al., 1989) :

$$\vec{f} = -k\vec{v} \qquad \text{with} \qquad k = n\pi\sqrt{\frac{4\mu\alpha q^2}{4\pi\epsilon_0}} \quad . \tag{3.2}$$

However this induced dipole regime holds as long as the drift velocity v is not too large($\gtrsim 10\,\mathrm{km\,s^{-1}}$) . At high velocity, the interaction approaches a hard sphere regime where the drag force is proportional to v^2 instead of v (BV07). Hence Ca II ions that encounter H I atoms at $\sim 1000\,\mathrm{km\,s^{-1}}$ fall in that regime. As the velocity decreases along successive collisions, the interaction finally enters the induced dipole regime. A correct description of the decelerating process of the Ca II ions implies therefore to be able to describe the interaction at *every* velocity, in particular in the intermediate velocity regime between the two above described extremes.

Using the *ab-initio* Gaussian 94 package (Frisch et al, 1995), we performed ROMP2 calculations of the interaction (BV07). Our ab-initio potential turns out to be consistent with the induced dipole approximation beyond 0.5 nm, but closer to 0.5 nm, it exhibits a repulsive wall providing a smooth transition towards the hard sphere regime. Given our potential, we numerically compute the resulting drag force at every velocity.

This description assumes implicitly that the encounters between the ion and the hydrogen atoms are elastic. Energetic collisions are likely to trigger inelastic processes. For impact velocities in the range 100–1000 $\mathrm{km\,s^{-1}}$, the energy available in the center of mass is huge, from 50 eV to 5000 eV, and is able to induce a large variety of inelastic processes such as inverse charge transfer, single or multiple electronic ionizations, etc...

All these inelastic processes will convert a part of the incoming kinetic energy into internal energy of the particles and thus increase the efficiency of the drag force. A simple way to treat possible ionization is to monitor the available kinetic energy $1/2\mu v^2$ before the collision in the inertial referential frame. Selecting close collisions for which the interaction departs from the induced-dipole model, we consider the opening of successive ionization channels when the energy is augmented. We model the ionization for H I and up to 7 electrons for Ca II, assuming an average energy loss $I_\mathrm{p} = 20\,\mathrm{eV}$ per electron.

In practice, we modify the smooth sphere model with the following prescription. If the available kinetic energy exceeds $k \times I_\mathrm{p}$ with $k \leq 8$ and if the closest approach between the two particles is less than 0.5 nm, the incoming kinetic energy is arbitrarily reduced by $k \times I_\mathrm{p}$. This causes the relative velocity after the encounter v' to be less than the initial velocity v.

The result of the force computation (see BV07 for details) in the various cases is shown in Fig. 2 (left) as a function of the relative velocity v. In the induced dipole approximation case, we find as expected $f \propto v$, and we see that this approximation is valid up to $v \simeq 20\,\mathrm{km\,s^{-1}}$. At the higher velocity regime, we have $f \propto v^2$ when the triplet potential is taken into account, corresponding to our smooth sphere regime. When ionization is also taken into account, the non-elastic character of the interactions adds an extra force term to the elastic smooth sphere case. Inelastic effects turns out to be particularly noticeable for $100\,\mathrm{km\,s^{-1}} \lesssim v \lesssim 1000\,\mathrm{km\,s^{-1}}$. This velocity regime concerns Ca II ions encountering a H I medium at about 100 AU.

Now we have an estimate of the drag force, we may derive in which conditions the H I medium is able to stop the Ca II ions. The question is to know which H I column density N_s the ions need to cross before being stopped. The ions arrive at initial velocity v_0 and encounter an H I medium with volume density n. They are accelerated by the radiation pressure P (locally constant). The equation of motion of an ion along its path will be

$$m\frac{\mathrm{d}v}{\mathrm{d}t} = P - nF(v) \qquad \Longleftrightarrow \qquad mv\frac{\mathrm{d}v}{\mathrm{d}N} = \frac{P}{n} - F(v) \quad . \tag{3.3}$$

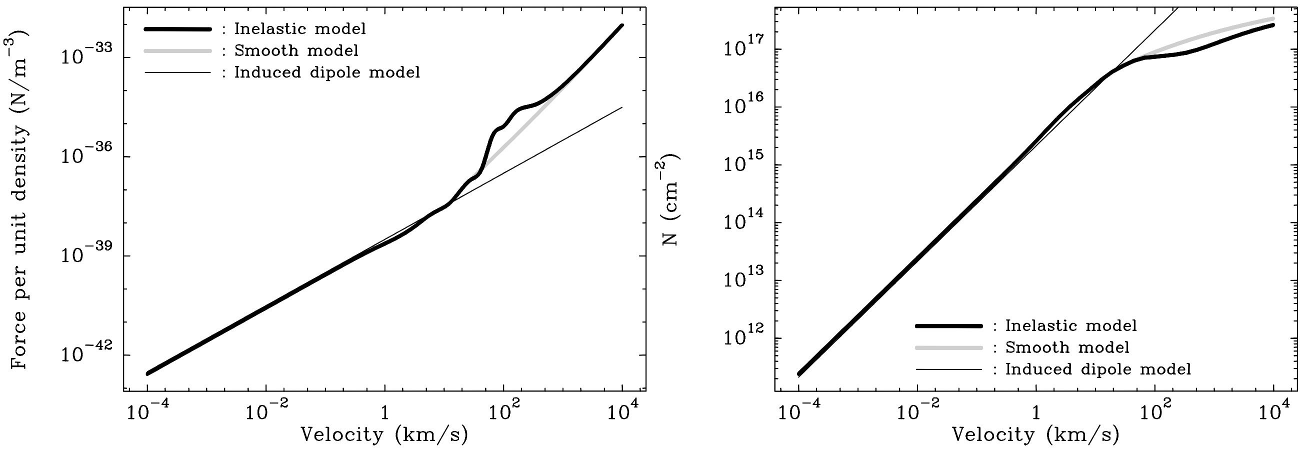

Fig. 2. Left : The drag force on Ca II ions due to a H I medium of unit density, as a function of the drift velocity v. **Right :** The resulting H I column density necessary to stop Ca II ions, as a function of the initial velocity v_0, as derived from Eq. 3.5.

where N is the H I comun density. The ions are not exactly stopped, but rather slowed down to an equilibrium velocity $v_{\rm eq}$ characterised by $nF(v_{\rm eq}) = P$. In practice this terminal velocity is low, so that the ions may be considered as stopped. The radiation pressure P at 100 AU on Ca II ions is $\sim 1.7 \times 10^{-29}$ N (35 times stellar gravity). Let us take the upper limit of $10^{18}\,{\rm cm}^{-2}$ for the hydrogen column density given by Lecavelier des Etangs et al. (2001), spread over a distance d. We derive a ratio

$$\frac{P}{n} = F(v_{\rm eq}) \simeq 2.5\,10^{-41} \times d({\rm AU})\,{\rm N\,m}^{-3} \qquad . \tag{3.4}$$

If we consider as a maximum value for d a few tens of AU, a comparison with Fig. 2 shows that $v_{\rm eq}$ is less than $1\,{\rm km\,s}^{-1}$ and that it falls well within the induced dipole regime.

The column density necessary to stop the ions read

$$N_{\rm s} = m \int_{v_{\rm eq}}^{v_0} \frac{v}{F(v) - F(v_{\rm eq})}\,{\rm d}v \simeq m \int_0^{v_0} \frac{v}{F(v)}\,{\rm d}v \qquad . \tag{3.5}$$

$N_{\rm s}$ is plotted on Fig. 2 (right) as a function of the initial velocity, for the various interaction models considered. As expected, in the induced dipole regime, we have $N_{\rm s} \propto v_0$, but at higher velocity, $N_{\rm s}$ is reduced by several orders of magnitude with respect to that crude estimate. The smooth sphere model causes $N_{\rm s}$ to stay below a few $10^{17}\,{\rm cm}^{-2}$ (asymptotically $N_{\rm s} \propto \ln v_0$). With $v_0 = 1000\,{\rm km\,s}^{-1}$, we predict $N_{\rm s} \simeq 10^{17}\,{\rm cm}^{-2}$. This is one order of magnitude below the upper limit to the H_2 column density towards β Pic (Lecavelier des Etangs et al., 2001). As suggested by our inelastic model, the inclusion of inelastic effects would further lower the required column density. Moreover, the collective effects decribed by Fernández et al. (2006), due to partial ionization of the neutral gas, are expected to enhance the braking process. $N_{\rm s}$ could thus be even less than the value we derive.

Hence we stress that the model we present here provides a plausible mechanism for stopping the Ca II ions at 100 AU from β Pic, in order to render them detectable in emission.

4 Conclusion

The presence of metallic ions at fairly high latitude over the mid-plane of the β Pic circumstellar disk, as observed by B04, can be very well explained as a consequence of the FEB process. Whenever the evaporating bodies enter the star grazing regime, they are subject to inclination oscillations up to $\sim 30 - 40°$. The Ca II ions released by the FEB during this phase start a free, almost radial expansion pushed by a strong radiation pressure, keeping track of their initial orbital inclination. This processa does not concerne Na I ions, as onec produced by the FEBs, they are quickly photoionized into Na II and subsequently no longer experience any noticeable radiation pressure. Hence we explain the absence of Na I emission at high latitude.

The Ca II ions reach the distance of $\sim 100\,\mathrm{AU}$ in about 1 yr with terminal velocities of $\sim 1000\,\mathrm{km\,s^{-1}}$. They need thus to be slowed down in order to gather at the star velocity and to form an observable line. This can be achieved if the ions encounter at that distance a neutral gaseous medium, in agreement with the conclusions of Fernández et al. (2006). A rough estimate of the incoming ion flux due to the FEB activity shows that it can account for the necessary heating source to render the lines observable.

In addition to the induced dipole drag force considered by Fernández et al. (2006), we estimated additional braking effects arising for rapid collisional velocities. If we consider the effect of repulsive core and inelastic interactions discussed in Sec 4.1.2 and 4.1.3, a column density of $10^{17}\,\mathrm{cm^{-2}}$ of H I is sufficient to stop the ions over a distance of a few AU, i.e. well below the upper detection limit of $10^{18}\,\mathrm{cm^{-2}}$ given by Lecavelier des Etangs et al. (2001).

The key parameter in this model is the distance ($\sim 100\,\mathrm{AU}$) at which the ions are stopped. In the gas drag model, we need to assume that no neutral medium is present at 30° inclination up to that distance. This would mean that the disk begins to significantly flare at that distance. This distance corresponds also to the expected outer edge of the planetesimal disk that produces the dust, according to Augereau et al. (2001). These two facts are probably related.

Our conclusion is thus that the proposed scenario is plausible (BV07). The FEB scenario is reinforced by the present analysis. The off-plane presence of some metallic species, and the absence of some others, appear as a natural consequence of the FEB scenario and of the mean-motion resonance model with a giant planet.

References

Augereau J.-C., Nelson R.P., Lagrange A.-M., Papaloizou J.C.B., Mouillet D., 2001, A&A 370, 447

Bailey M.E., Chambers J.E., Hahn G., 1992, A&A 257, 315

Beust H., Lagrange-Henri A.-M., Vidal-Madjar, A., Ferlet, R., 1989, A&A 223, 304

Beust H., Lagrange-Henri A.-M., Vidal-Madjar, A., Ferlet, R., 1990, A&A 236, 202

Beust H., Lagrange A.-M., Plazy F. Mouillet D., 1996, A&A 310, 181

Beust H., Morbidelli A., 1996, Icarus 120, 358

Beust H., Lagrange A.-M., Crawford I.A., et al., 1998, A&A 338, 1015

Beust H., Morbidelli A., 2000, Icarus 143, 170

Beust H., Valiron P., 2007, A&A 466, 201

Brandeker A., Liseau R., Olofsson G., Fridlund M., 2004, A&A 413, 681 (B04)

Ferlet R., Hobbs L.M., Vidal-Madjar A., 1987, A&A 185, 267

Fernández R., Brandeker A., Wu Y., 2006, ApJ 643, 509 (F06)

Frisch M.J., Trucks G.W., Schlegel H.B., et al., 1995, Gaussian 94, Revision E.2, Gaussian Inc. (Pittsburgh PA)

Kozai Y., 1962, AJ 67, 591

Lagrange A.-M., Beust H., Mouillet D., et al., 1998, A&A 330, 1091

Lecavelier des Etangs A., Vidal-Madjar A., Roberge A., et al., 2001, Nature 412, 706

McDaniel E.W., 1964, in *Collision phenomena in ionized gases*, John Wiley & sons

Olofsson G., Liseau R., Brandeker A., 2001, ApJ 563, L77

Petterson O.K.L., Tobin W., 1999, MNRAS 304, 733

Smith B., Terrile R., 1984, Sci 226, 1421

Thébault P., Beust H., 2001, A&A 376, 621

Vidal-Madjar A., Lagrange-Henri A.-M., Feldman P.D., et al., 1994, A&A 290, 245