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ECCENTRICITY AND INCLINATION EVOLUTION OF HOT PROTOPLANETARY EMBRYOS IN PROTOPLANETARY DISCS

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RESUMEN

Después de un muy breve repaso de la literatura sobre interacciones gravitatorias entre discos y planetas, nos interesamos en embriones planetarios calentados por el bombardeo de planetesimales o *pebbles*. Éstos irradian el disco circundante y generam cambios de temperatura y densidad en su vecindad, en adición a los que inducen por su gravedad. A su vez, la perturbación de densidad así generada ejerce una fuerza sobre el embrión. Mediante un análisis en el regimen lineal, así como simulaciones numéricas, investigamos el impacto de esta fuerza sobre la eccentricidad e inclinación de los embriones calientes. En lugar de la invariable amortigüación que estos elementos orbitales sufren cuando el embrión no libera calor, encontramos que eccentricidad e inclinación son al contrario excitados por la fuerza de calentamiento, hasta valores comparables con la relación de aspecto del disco.

ABSTRACT

After a very brief review of the literature on planet-disc tidal interactions, we focus on planetary embryos that are heated by planetesimal bombardment or pebble accretion. They irradiate the surrounding disc and thereby induce temperature and density perturbation in their neighbourhood, in addition to the disturbances triggered by gravity. In return, the perturbation of density induces a force on the embryo. Through an analysis in the linear regime and through numerical simulations, we investigate the impact of this force on the eccentricity and inclination of hot embryos. Instead of the consistent decay that these orbital elements suffer when the embryo does not release heat, we find here that they are on the contrary excited to values comparable with the aspect ratio of the disc.

Key Words: gravitation — hydrodynamics — planets and satellites

1. INTRODUCTION

Nascent planets interact with their progenitor disc. Not only does this interaction feed the planets and make them grow, it also considerably alters their orbits. For several decades this aspect of planet-disc interactions has been tackled by assuming that the planets solely perturb the disc by gravity. The feed back of the gravitational disturbances on the orbits of the planets, or disc's tide, gives rise to a considerable variety of effects that we very briefly summarise in section 2. Not all the perturbation imparted by a protoplanet to the disc is of gravitational origin, however. Benítez-Llambay et al. (2015) have found that the energy released in the disc by an embryo heated by solid accretion leads to significant perturbations in the planet vicinity, in addition to those due to gravity, which can have a profound impact on its orbital evolution. More recently, Masset & Velasco Romero (2017) have analysed the impact of the heat released by a perturber which travels across a uniform and opaque gas at rest. Such a setup is simpler to analyse than that a planet embedded in a protoplanetary disc, because of the lack of Keplerian shear. They found that a hot trail is created in the perturber's vicinity. The gas in this trail is underdense, which results in a force pushing the planet in its direction of motion (the push from the front material is larger than the pull of the depleted rear material). We summarise the main properties of the force due to heating in section 3. In section 4, we show by means of numerical simulations that hot, Earth-sized embryos experience an eccentricity (inclination) growth as a result of heat release. Namely, embryos initially nearly circular and nearly coplanar with the disc can reach eccentricities and inclinations comparable to the disc's aspect ratio over timescales of $O(10^3)$ yrs, when they have a mass doubling time of $O(10^5)$ yrs.

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2. GRAVITATIONAL INTERACTIONS BETWEEN THE DISC AND A NON-LUMINOUS PLANET

The gravitational interaction between a thin, gaseous disc and a point-like massive object orbiting within the disc has initially been considered by Goldreich & Tremaine (1979, 1980), who noticed that planets embedded in their protoplanetary discs would experience a variation of their semi-major axis (later called migration) on timescales orders of magnitude shorter than the typical lifetime of the disc. Papaloizou & Lin (1984) and Lin & Papaloizou (1986a,b) examined the interaction between the protoplanetary disc and a giant planet, showed that the latter carves a gap in the disc, and formulated a criterion for gap opening, which was subsequently refined by Crida et al. (2006). More than two decades of efforts have been dedicated to the determination of an accurate derivation of the migration speed as a function of the planetary mass and of the disc parameters (mostly its aspect ratio, its surface density, its slopes of surface density and temperature, its effective viscosity and thermal diffusivity). On the low end of the protoplanetary mass range, Tanaka et al. (2002) have determined this speed by semi-analytical calculations in the linear approximation, for low-mass planets embedded in globally isothermal discs. The isothermal assumption was relaxed when it became apparent that the disc's thermodynamics plays an important role on migration (Paardekooper & Mellema 2006; Paardekooper & Papaloizou 2008; Baruteau & Masset 2008). These works were focused on a detailed description of a specific component of the tidal torque (namely the corotation torque) and led to detailed formulae for the torque exerted on low-mass planets in discs as a function of the aforementioned parameters (Masset & Casoli 2010; Paardekooper et al. 2011). Migration of low-mass planets ($\lesssim 5\ M_\oplus$) and intermediate mass planets ($5-50\ M_\oplus$) is mostly directed toward the central star, although domains of outward migration may be found for intermediate mass planets (Lega et al. 2015). The limits of these domains, and their mere existence, depend however on the disc's effective viscosity, which controls the magnitude of the corotation torque (Balmforth & Korycansky 2001; Masset 2001; Masset & Casoli 2010; Paardekooper et al. 2011) and which is poorly known. The thermodynamical properties of the disc may also be important on components of the torque other than the corotation torque. Lega et al. (2014) report the finding of cold, dense and asymmetric lobes of gas that form in the planet vicinity in discs with finite thermal diffusivity. This effect has never been incorporated so far in torque expressions. On the high end of the planetary mass range, corresponding typically to Saturn-mass planets and above, most studies have been tackled numerically, as the gas flow is markedly non-linear for such planetary masses (Korycansky & Papaloizou 1996). Planet migration in this regime, named type II migration, was initially considered locked in the viscous disc evolution (Ward 1997). This could occur if the planetary gap partitioned the disc into an inner and outer parts which would not exchange material. The gas can flow however across the gap (Kley 1999; Dürmann & Kley 2016), which leads to a slower migration (Ivanov et al. 1999; Nelson et al. 2000). Much efforts have been devoted to obtain the radial dependence of the surface density in the gap as a function of the planet mass and disc parameters (Fung et al. 2014; Duffell 2015), in particular because this could help interpret observations. The torque arising from orbit crossing material depends on the relative drift between the viscous disc and the migrating planet. This exerts a feed back on migration, which is positive, and may yield to fast migration, named type III. Initially found for sub-giant planets that carve significant dips in the disc (Masset & Papaloizou 2003), it has been extended to lower mass planets (Paardekooper 2014).

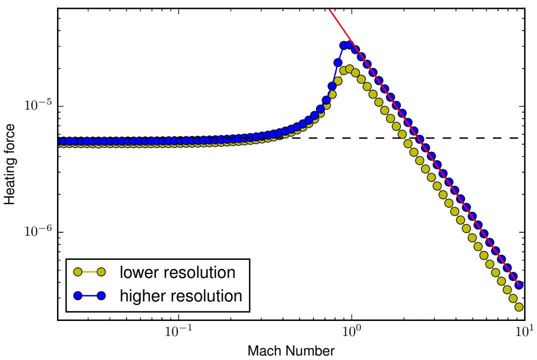

Fig. 1. Heating force on a perturber as a function of its Mach number. Two different resolutions have been employed, yielding different effective values of $r_{\min}$. The darker curve shows the most resolved case. The horizontal dashed line shows the result of Eq. (1), and the tilted solid line (in red on the electronic version) shows a V^{-2} dependence such as the one expected from Eq. (2), with an arbitrary scaling factor.

Planet-disc interactions also affect the eccentricity and inclination of embedded planets. A planet passing at apocentre is slower than the surrounding material, and experiences a force frontward, whereas

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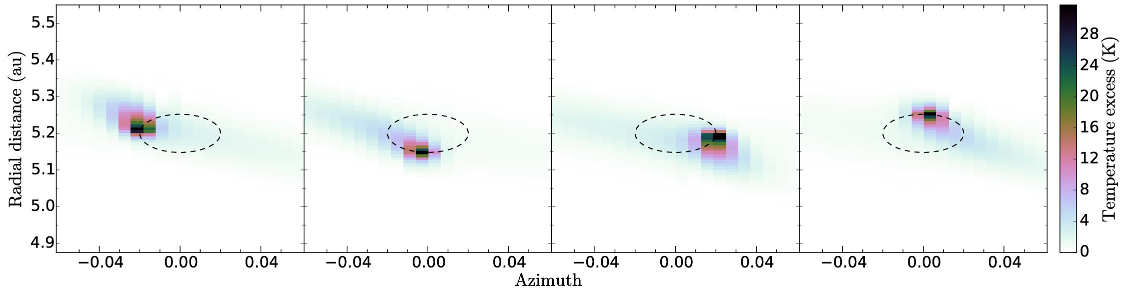

Fig. 2. Temperature excess due to the heat released by a luminous, eccentric planet, obtained by subtracting the midplane temperature in a run with a non-luminous planet from the midplane temperature in a run with a luminous planet. The ellipse shows the planet's epicycle (its eccentricity is 0.01). The numerical simulations have been performed with the FARGO3D code, with a setup similar to that of Benítez-Llambay et al. (2015), for an Earth-mass planet with a mass doubling time of 10^5 kyrs.

the opposite holds at pericentre. As it spends more time at apocentre, it tends to gain angular momentum with respect to a similar planet on a nearly circular orbit. This angular momentum is used to circularise the orbit, rather than increase its semi-major axis (Masset 2008). The damping rate of eccentricity of a low-mass planet has been worked out in isothermal discs by Artymowicz (1993) and Tanaka & Ward (2004), and found to be shorter than the migration time scale by a factor of h^2 (h being the disc's aspect ratio). Tanaka & Ward (2004) have also worked out the time behaviour of the inclination of low-mass planets and found that it is damped on a timescale similar to that of the eccentricity. The behaviour of the eccentricity of a low-mass planet when it has a value comparable to or larger than the disc's aspect ratio has been worked out by Papaloizou & Larwood (2000). All these analytical works have been confirmed and extended by numerical simulations (e.g. Cresswell et al. 2007). It has been suggested that large mass planets (with gaps) could experience an eccentricity growth as a result of their interaction with the disc (Papaloizou et al. 2001; Ogilvie & Lubow 2003; Goldreich & Sari 2003). The eccentricity budget of these objects can indeed be reversed by the saturation of the eccentric corotation resonance. These predictions have only very recently received confirmation from numerical simulations (Duffell & Chiang 2015). The inclination of giant planets, on the contrary, always decays as the interaction with the disc tend to realign the disc and the orbit (Xiang-Gruess & Papaloizou 2013).

3. HEATING FORCE ON A LUMINOUS PERTURBER

We sum up here the results obtained by Masset & Velasco Romero (2017) for a perturber of mass M and luminosity L in uniform motion at velocity V in a homogeneous gas at rest adiabatic sound speed c, adiabatic index γ and thermal diffusivity χ. One can work out separately, in the linear regime, the force arising from the gas heating (*i.e.* the force on the hot perturber minus the force on a similar, non-luminous perturber). This *heating force* has same direction as the motion and, in the low Mach number regime, has expression:

$$F = \frac{\gamma(\gamma-1)GML}{2\chi c^2}. \tag{1}$$

Remarkably, it does not depend on the perturber's velocity. In the limit of large Mach numbers, the force is given by:

$$F = \frac{(\gamma-1)GML}{\chi V^2} f(r_{\min} V/4\chi), \tag{2}$$

where f is a function that diverges logarithmically as its argument tends to zero. We show in Fig. 1

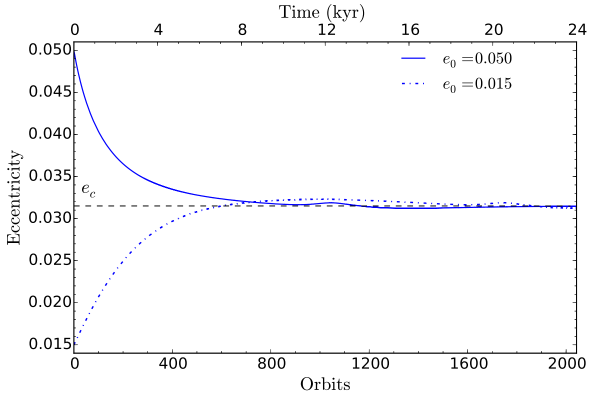

Fig. 3. Eccentricity behaviour as a function of time for an Earth mass planet, for the same setup as Fig. 2.

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a confirmation of these expectations from numerical simulations realised on a Cartesian mesh with the public hydrocode FARGO3D (Benítez-Llambay & Masset 2016).

4. ECCENTRICITY AND INCLINATION DRIVING OF LOW-MASS, LUMINOUS PLANETS

We present in Fig. 2 the temperature excess arising from the heat released by a low-mass, eccentric planet, at the midplane of the protoplanetary disc. The hot trail that appears is marginally smaller than the radial excursion of the planet, and resembles the hot plume that appears in the absence of shear, responsible for the heating force summarised in the previous section.

The force exerted by this hot trail pushes the planet on its epicycle and drives the eccentricity, until it is balanced by the disc's tide, at which point the eccentricity saturates. We comment that when the eccentricity is much smaller than 0.01 (in this specific setup) the effect of the shear on the hot plume cannot be neglected and the simple interpretation above does not hold. The eccentricity is nevertheless also excited in this regime, and can grow to large values from an initial value as small as 10^{-6}. Fig. 3 shows the eccentricity of the planet as a function of time, for two different values of the initial eccentricity. In the two cases the eccentricity is found to converge at larger time toward $e_c \approx 0.031$, a value that is only marginally smaller than the disc's aspect ratio, which amounts to $h = 0.042$ in this simulation. A similar behaviour (not shown here) is found for the inclination, which saturates at a value slightly smaller than the eccentricity ($i_c \approx 0.028$). The asymptotic values of the eccentricity and inclination are found to depend on the luminosity to mass ratio of the planet. On the long term, we find that the eccentricity and inclination are coupled and do not evolve independently. The details and origin of this coupling will be presented elsewhere (Eklund & Masset, in prep.). We comment that the hot trail in the simulations presented here is poorly resolved and the force it exerts on the planet is probably underestimated. This stresses the need for very high resolution calculations, for which nested meshes are probably the way to go.

REFERENCES

Artymowicz, P. 1993, ApJ, 419, 166
Balmforth, N. J. & Korycansky, D. G. 2001, MNRAS, 326, 833
Baruteau, C. & Masset, F. 2008, ApJ, 672, 1054
Benítez-Llambay, P., Masset, F., Koenigsberger, G., & Szulágyi, J. 2015, Nature, 520, 63
Benítez-Llambay, P. & Masset, F. S. 2016, ApJS, 223, 11
Cresswell, P., Dirksen, G., Kley, W., & Nelson, R. P. 2007, A&A, 473, 329
Crida, A., Morbidelli, A., & Masset, F. 2006, Icarus, 181, 587
Duffell, P. C. 2015, ApJ, 807, L11
Duffell, P. C. & Chiang, E. 2015, ApJ, 812, 94
Dürmann, C. & Kley, W. 2016, ArXiv e-prints
Fung, J., Shi, J.-M., & Chiang, E. 2014, ApJ, 782, 88
Goldreich, P. & Sari, R. 2003, ApJ, 585, 1024
Goldreich, P. & Tremaine, S. 1979, ApJ, 233, 857
—. 1980, ApJ, 241, 425
Ivanov, P. B., Papaloizou, J. C. B., & Polnarev, A. G. 1999, MNRAS, 307, 79
Kley, W. 1999, MNRAS, 303, 696
Korycansky, D. G. & Papaloizou, J. C. B. 1996, ApJS, 105, 181
Lega, E., Crida, A., Bitsch, B., & Morbidelli, A. 2014, MNRAS, 440, 683
Lega, E., Morbidelli, A., Bitsch, B., Crida, A., & Szulágyi, J. 2015, MNRAS, 452, 1717
Lin, D. N. C. & Papaloizou, J. 1986a, ApJ, 307, 395
—. 1986b, ApJ, 309, 846
Masset, F. S. 2001, ApJ, 558, 453
Masset, F. S. 2008, in EAS Publications Series, Vol. 29, EAS Publications Series, ed. M.-J. Goupil & J.-P. Zahn, 165–244
Masset, F. S. & Casoli, J. 2010, ApJ, 723, 1393
Masset, F. S. & Papaloizou, J. C. B. 2003, ApJ, 588, 494
Masset, F. S. & Velasco Romero, D. A. 2017, MNRAS, 465, 3175
Nelson, R. P., Papaloizou, J. C. B., Masset, F. S., & Kley, W. 2000, MNRAS, 318, 18
Ogilvie, G. I. & Lubow, S. H. 2003, ApJ, 587, 398
Paardekooper, S., Baruteau, C., & Kley, W. 2011, MNRAS, 410, 293
Paardekooper, S.-J. 2014, MNRAS, 444, 2031
Paardekooper, S.-J. & Mellema, G. 2006, A&A, 459, L17
Paardekooper, S.-J. & Papaloizou, J. C. B. 2008, A&A, 485, 877
Papaloizou, J. & Lin, D. N. C. 1984, ApJ, 285, 818
Papaloizou, J. C. B. & Larwood, J. D. 2000, MNRAS, 315, 823
Papaloizou, J. C. B., Nelson, R. P., & Masset, F. 2001, A&A, 366, 263
Tanaka, H., Takeuchi, T., & Ward, W. R. 2002, ApJ, 565, 1257
Tanaka, H. & Ward, W. R. 2004, ApJ, 602, 388
Ward, W. R. 1997, Icarus, 126, 261
Xiang-Gruess, M. & Papaloizou, J. C. B. 2013, MNRAS, 431, 1320