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Interactions between an asteroid type body and a protoplanet within a protoplanetary accretion disc: 3D SPH simulations

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Abstract. Migration of protoplanets in an accretion disc of a forming star is currently the most believable scenario for the formation of planetary systems, but much work still has to be done to understand the migration mechanisms due to the planet-disc interactions. Attention is here focused on the evolution of the orbit of an asteroid type body with an initially tilted orbit, under the influence of the gravitational interaction with the accretion disc and with a more massive protoplanet (both Jupiter-like and Earth-like protoplanets are considered). A SPH based three-dimensional model is used to analyse this physical scenario. Both "internal fragment - external protoplanet" and "external fragment - internal protoplanet" configurations are considered.

1. Introduction

Nearly 300 extrasolar planets have been detected (http://www.obspm.fr/planets; http://exoplanets.org) till now and most of them are massive (Jupiter-like) planets with small (fractions of AU) semi-major axes (Perryman, 2000; Udry & Santos, 2007). Theoretical models for the formation of planetary systems are then mostly based on the crucial role of an accretion disc around a forming young star, where the disc provides both the material for the forming planets and the interactions responsible for the migration of the protoplanets (Artymowicz, 2004). These models have to account for a correct balance between the evolutionary times of their main components: the gas and dust of the disc and the protoplanets. Regarding the protoplanets, the two involved times are concerned with their formation via hierarchical accumulation of smaller bodies, and their eventual inward or outward migration. The main known features of disc-planet interactions can be deduced from analytical studies and from numerical simulations (D'Angelo et al. (2003b); Lin & Papaloizou (1986); Goldreich & Tremaine (1980); Papaloizou et al. (2007) and references therein). The action of gravitational torques on the planet's orbit and the transport of angular momentum due to viscosity are reported as the main mechanisms causing planet migration. Usually, two main migration regimes are described: *type I* for Earth-like planets and

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type II for Jupiter-like planets. Downward migration times of the order of $10^4 - 10^5$ years, starting from about 5 AU are currently predicted.

Since most of the models have been built in two-dimensional way, there is still the need to scrutinise the effect of disc-planet interaction in three dimension, particularly if the orbit of a forming protoplanet does not lie in the average accretion disc plane. Moreover current models very often uses laminar disc motion and Keplerian distribution of gas velocity as acceptable hypotheses, while the role of turbulence in planet migration times still has to be studied (Nelson & Papaloizou (2004) and reference therein). Not many 3D simulations are available in literature to scrutinise the matter of planet formation within an accretion disc model (see for example: D'Angelo et al. (2003a); Cresswell et al. (2007), 3D simulations are the only way to explore the effects on protoplanet's orbit inclination of the interaction with the accretion disc. Here an exploratory study on these effects is proposed, with the use of a Lagrangian SPH code, as other calculations present in the literature are based on grid models. The evolution of the orbit of a "small" fragment with an initial tilted orbit is focused here. This study is not directly aimed at evaluating migration times of nearly formed protoplanets, it is instead concerned with effects of gravitational interaction between the accretion disc, a small asteroid type body and a much bigger protoplanet (Jovian or earth like) on the evolution of the fragment orbit. This work is complementary to the one presented by Costa et al (2009) with similar models, without the contribution of the protoplanet.

2. Accretion disc model asteroid-planet and asteroid-disc interactions

Simulations are performed through a 3D Cartesian code based on the Smoothed Particle Hydrodynamics (SPH) method (Monaghan, 1992), details are presented also in Costa et al (2009); Costa et al. (20010). The initial structure of our disc is created through the injection of particles at point-like positions (injectors) along circles concentric with the central star, at a distance of 130 stellar radii. Particles have initial tangential velocities set by choosing a value for the specific angular momentum J (see table 1 for the chosen J values). All the three choices give a sub-Keplerian feature to the velocity distribution of the accretion disc (see Costa et al. (20010) for a discussion of this topic). There are 3 injectors rings that form the disc structure: one lies exactly on the xy plane, the other two lie on planes parallel to the xy plane, one above and one below it, at a distance equal to the SPH smoothing length h. Gas pressure and artificial viscosity (pressure contribution) are included in our models together with gravitational interactions (excluding self-gravitation).

Dimensionless quantities are used, and reference physical units are the following:

1. the initial stellar mass M_0;
2. the stellar radius R_0;
3. the Keplerian orbital period $T_0 = \sqrt{\frac{R_0^3}{GM_0}}$ for an orbit of radius R_0 around a star of mass M_0.

The computational domain is a cylinder, extended in the xy plane within a distance of 140 to the central star (base radius) and within $|z| < 140/3$ as regards the height of the cylinder. All models in this study are evolved including two objects, a protoplanet and and asteroid. The two objects are inserted in the xy plane after the accretion disc is already formed and evolved until the number of particles becomes steady (on a time average, since quasi periodical variations due to turbulence are observed), with a value of $\sim 2 - 3 \times 10^5$ using a *smoothing length* $h = 0.3$ (Monaghan, 1992). The initial distances of the two objects are reported in table 1. The peculiar choices for D1 and D2 in table 1 allow us to distinguish two groups of models: models labelled *a* and *c* which have the protoplanet external with respect to the asteroid, and models labelled *b* and *d* in which the protoplanet is internal instead.

In all models the protoplanet has an initial Keplerian velocity with zero eccentricity and the orbit lying on the xy plane, the asteroid has

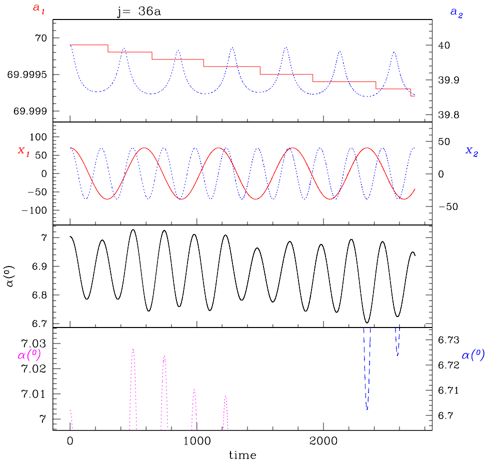

Fig. 1. Orbital parameters as a function of time for model 36a (see table). Starting from the top rectangle you find here: the semi-major axis a; the x coordinate; the angle α between the asteroid angular momentum and the z axis; a zoom of the angle graph to show relative maxima (magenta dotted line) and relative minima (blue dashed line). In the first two rectangules, data related to the protoplanet are plotted in red (solid line), and those related to the asteroid are in blue (dotted line).

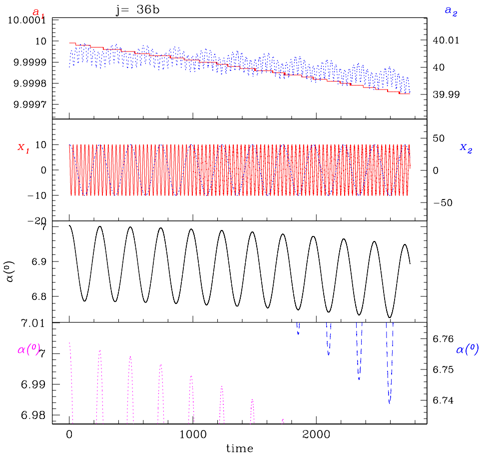

Fig. 2. Orbital parameters evolution for model 36b. See fig. 1 for details.

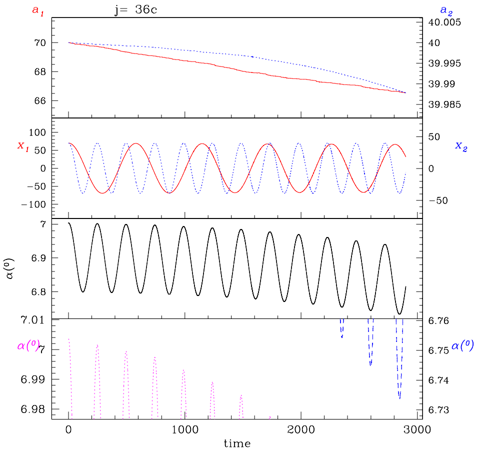

Fig. 3. Orbital parameters evolution for model 36c. See fig. 1 for details.

circular tilted orbit, with an initial angle a between its angular momentum vector and the z axis of 7^0.

3. Preliminary results

Figures 1-4 show some preliminary results for models 36$a-d$ (see table 1. Each figure gives the semi-major axis a of the two objects, their x coordinates, the angle α between the asteroid angular momentum and the z axis and a zoom on the relative extrema of the same angle as a function of time.

The mutual influence between the protoplanet and the asteroid is clearly visible in the "a" and "b" models, where the protoplanet has the biggest (Jovian) mass. A steady decrease of a is observed and an oscillation of the asteroid parameters is visible. This oscillation is linked to two different causes: the orbiting of the asteroid inside the disc, with the periodical crossing of the xy plane; the interaction of the asteroid with the protoplanet. A deeper analysis of the link between all the periods still needs to be done, and it will be described in a forthcoming paper together with the results concerning other models. Less visible, at least at this stage, is the effect of the protoplanet on the asteroid orbit for models "c" and "d", where the protoplanet mass is Earth-like.

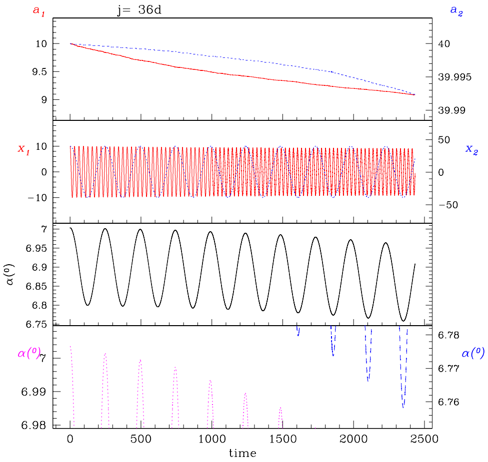

Fig. 4. Orbital parameters evolution for model 36d. See fig. 1 for details.

Table 1. List of computed models, with their identifying labels (first column). The second column gives the mass of the protoplanet included in the simulation (the asteroid has in all models a mass of 10^{-11}); the third column gives the specific angular momentum J of injected gas particles (the Keplerian value would be ~ 71), the fourth and fifth columns give the initial distances of the protoplanet and the asteroid to the central star.

Model	Mass 1	J	D1	D2
18a	10^{-3}	18	70	30
18b	10^{-3}	18	10	30
18c	10^{-7}	18	70	30
18d	10^{-7}	18	10	30
36a	10^{-3}	36	70	40
36b	10^{-3}	36	10	40
36c	10^{-7}	36	70	40
36d	10^{-7}	36	10	40
54a	10^{-3}	54	100	65
54b	10^{-3}	54	40	65
54c	10^{-7}	54	100	65
54d	10^{-7}	54	40	65

In models where the protoplanet is more internal than the asteroid, the asteroid orbit seems more unstable. All models show a tendency towards a decrease of the semi-major axis of both objects, and a decrease of the tilt angle α. This has also been observed in another study by Costa et al (2009) without the protoplanet. In fact, the results of the models with the Earth-like protoplanet, which exerts a lower gravitational attraction than the Jupiter-like planet, are similar to those produced by Costa et al (2009). Further analysis will be conducted while bringing further in time our calculations.

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