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Evolution of the orbit of an asteroid type body within a protoplanetary accretion disc: 3D SPH simulations

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Abstract. Migration of protoplanets within an accretion disc of a forming star seems to be the basic scenario for planetary systems formation. Many details concerning the dragging mechanisms, times and the dominant physical interactions between the protoplanets and the accretion disc are still debated. We report here the results of a study based on 3D Smoothed Particle Hydrodynamic (SPH) simulations, concerning the evolution of the orbital parameters of an asteroid type body embedded in an inviscid accretion disc, with an initially tilted orbit. Both rapid periodic variations of the tilt angle between the fragment angular momentum and the disc mean angular momentum, and a slow monotonic decrease are observed.

1. Introduction

Migration of proplanets inside a protostar accretion disc is the most accredited scenario for the formation of planetary systems. Of the nearly 300 extrasolar planets currently detected (http://www.obspm.fr/planets; http://exoplanets.org), most are massive (Jupiter-like) planets with small (fractions of AU) semi-major axes (Perryman 2000; Udry & Santos 2007). As direct formation of such planets at these distances to the central star is very unlikely, orbital evolution of the protoplanets and migration after formation at larger distances are crucial for a self-consistent model. These models need to account for a correct balance between the evolutionary times of their main components: the gas and dust of the disc and the protoplanets. The main known features of accretion disc-planet interactions, derived from analytical studies and from numerical simulations can be deduced from Artymowicz (1993, 2004); Goldreich & Tremaine (1980); Lin & Papaloizou (1986b); D'Angelo et al. (2003b); Papaloizou et al. (2007); Ward (1997), and references therein.

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Since most of the models were built in two-dimensional way, there is still the need to scrutinise the effect of disc-planet interaction in three dimensions, particularly if the orbit of a forming protoplanet does not lie in the same plane as the average accretion disc. 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 needs to be studied (Nelson & Papaloizou (2004) and reference therein). In the presence of turbulent hydrodynamics, the evolution of the accretion disc may appear different if simulated in 2D or 3D, since the few 3D simulations present in literature can show (D'Angelo et al. 2003b; 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. 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 protoplanet, it is instead concerned with effects of gravitational interaction between the accretion disc and a small asteroid type body on the evolution of the fragment orbit.

2. The models

Simulations are performed with a 3D Cartesian code, based on the Smoothed Particle Hydrodynamics (SPH) method (Monaghan 1992) (see Costa et al. (2010) for some details and for the definition of dimensionless units). The initial structure of the accretion 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 angular momentum per unit mass J. Three choices are made here for J: 18 , 36, 54. All the three choices give a sub-Keplerian feature to the velocity distribution of the accretion disc, so that injected particles start lowering their distance to the centre, until they "hit" the centrifugal barrier, and they may give rice to the development of shock fronts (Costa et al. 2010). There are 5 injectors rings that forms the disc structure: one lies exactly on the xy plane, the other 4 on planes parallel to xy, at a distance of h or $2h$. Two of them are above xy and the other two are below. This conditions give a real 3D structure to the disc. Particles are eliminated when they are close to the star or outside of the cylindrical computational domain ($\sqrt{x^2+y^2} < 140$ and $|z| < 140/3$). Even if a steady state for the accretion disc cannot be reached due to turbulence and shock waves propagation, the time averaged particle population stops growing at some point, with values of $\sim 2x10^5 - 10^6$ particles, depending on the model, when using a smoothing length h of 0.3, the planetesimal is then inserted and its orbital parameters are tracked during the simulation. The model includes gravitational forces (no disc self-gravitation), artificial viscosity (pressure contribution), and pressure component to the interaction between the asteroid and the gas (for some models only, see table 1). The initial conditions for the models are summarised in the table 1. Position is chosen in order to have the fragment inside the

Table 1. Scheme of the computed models. The model identifying label is in the 1st column, the initial "tilt angle" in 2nd column, 3rd column says if the model is includes the pressure contribution between the asteroid and the disc gas, 4th and 5th columns report the initial asteroid distance to the central star and the corresponding period. See Costa et al. (2010) for definition of dimensionless units.

model	$\alpha^{(0)}$	Asteroid pressure	D	Period
18a	7	no	30	164.3
18b	7	yes	"	"
18c	30	no	"	"
18d	30	yes	"	"
36a	7	no	40	253.0
36b	7	yes	"	"
36c	30	no	"	"
36d	30	yes	"	"
54a	7	no	65	524.1
54b	7	yes	"	"
54c	30	no	"	"
54d	30	yes	"	"

Table 2. Decrease rates for the "tilt angle" α (see text) for some of the computed models.

model	$\Delta\alpha$ ($^0/orbit$)
18a	0.001
18c	0.02
36a	0.005
36c	0.01
54a	0.07
54c	0.009

most populated disc zone (near the centrifugal barrier for gas particles, located according the specific angular momentum), while the initial velocity is chosen in order to have a circular (eccentricity=0) orbit, tilted with respect to the disc average plane, by an initial angle of about $\alpha = 7^0$. The mass of the particles is set to 10^{-11} (in units of M_0), which means that the total mass of the disc can be about 10^{-5}. The planetesimal fragment has about the same mass, which, referring to solar values as an example, gives a fragment of about 10^{19} Kg, which could correspond to a $\sim$ 500 – 1000 Km sized asteroid. Given this low mass for the fragment, no capture of gas particles is included in the models, while particles are deleted only when they are close to the star or when they go outside of the computational domain. Some models include a pressure interaction between the asteroid and the disc gas, through the inclusion of an SPH particle associated to the asteroid, but the results for these models are not shown here since thy are still under development and analysis.

3. Preliminary results

Until now, the models have been evolved for about 5-10 orbits of the asteroid and the orbital parameters have been tracked along the whole simulation. Figures 1-4 report some of these parameters: a (semi major axis of the fragment orbit); α (red) the angle between the fragment angular momentum and the z axis, used to analyse changes of orbit inclination; α (green) relative minima, zoomed in the "a-time" graph (green lines) in order to show the non-periodical variation of the asteroid orbit inclination; α (blue) relative maxima, zoomed in the "a-time" graph (blue lines).

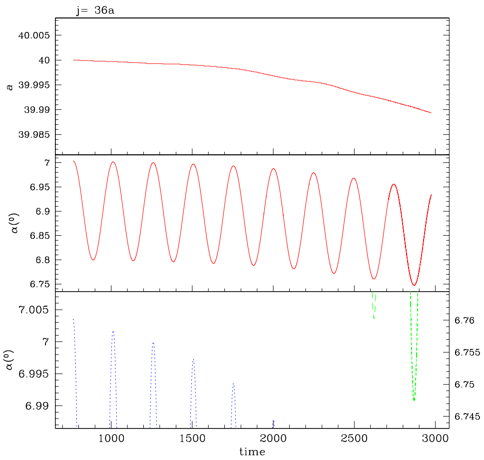

Fig. 1. Model 36a (particle specific angular momentum $j = 36$), orbital parameters evolution: The top square reports the semi-major axis "a" in units of the stellar radius; the central square reports the angle α between the asteroid angular momentum vector and the z axis; the bottom square reports the same angle zoomed to better show relative maxima (blue dotted lines) and relative minima (green dashed lines).

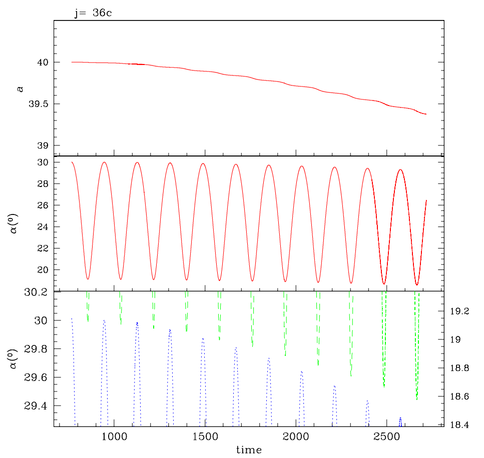

Fig. 2. Results for model 36c (see caption of fig. 1for details).

Models with a stronger sub-Keplerian structure ($j = 18$) require more computational

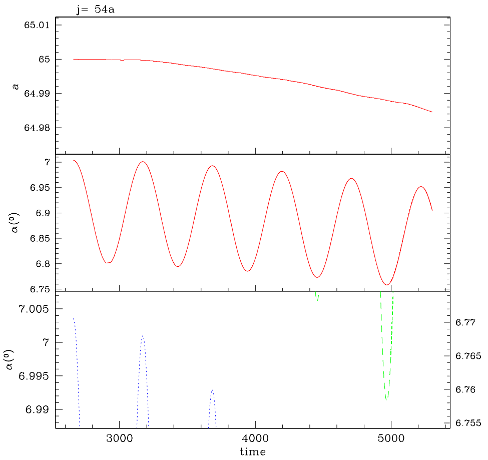

Fig. 3. Results for model 54a (see caption of fig. 1for details).

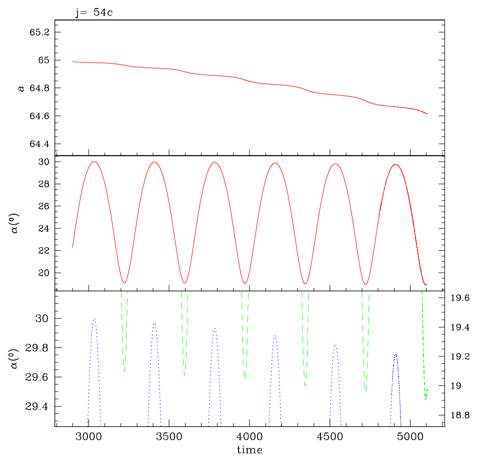

Fig. 4. Results for model 54c (see caption of fig. 1for details).

time despite the smaller number of particles in the disc, due to smaller time step size induced by thermal energy conditions of the disc gas. All models show a quasi-periodical variation of the inclination angle of the asteroid angular momentum with the z axis, linked to the periodical crossing of the disc plane by the asteroid. A slow non periodical variation of the angle is also visible, since after each orbit the relative maximum of a and the relative minimum show a slow decrease, as suggested by Cresswell et al. (2007). Currently the average decrease rates reported in table 2 are observed for α. From figures 1 and 2, where models 36a and 36c are represented, it seems that the decrease rate of α is characterised by an acceleration accompanied by a decrease of the semi-major axis a. Thus, decrease rate is not necessarily constant. We can see that the decrease rate is higher for model with an initial higher inclination (30^0) and for model with higher j values. Results for models 18b, 18d, 36b, 36d, 54b, 54d, are not currently shown since they are still under deep analysis, but we can anticipate that the fragment behaviour is much less stable and regular, due to the strong gas interaction between the asteroid and the gas particles of the disc. We will show them in a future work, together with a more detailed description of the disc gas flows and turbulent structures.

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