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2D SPH simulations of planet-disc interactions

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Abstract. Current theories on planetary formation establish that massive objects accrete gaseous envelopes, becoming gaseous planets if the accretion process proceeds before the accretion disc dissolution. One of the unsolved problems is that the planet formation is contextual to their quick migration towards the central star, due to the protoplanets-disc interaction, on a timescale lower by an order of magnitude than that of gas accretion onto the protoplanet. These arguments have been recently broached using N-body and/or Eulerian fluid-dynamics codes, mainly in 2D, or a mixing of them. In this work, 2D simulations with a SPH code are performed, to study the migration of one protoplanet. The goal is to scrutinise the protoplanet dragging as a function of planet's mass.

Key words. Stars: planetary systems: formation, protoplanetary discs – Planets and satellites: formation

1. Introduction

More than 200 extrasolar planets have been detected (http://www.obspm.fr/planets; http://exoplanets.org). Current theories on planet formation (Artymowicz 2004; Terquem et al. 2000) have often the need to account for a correct balance between the accretion disc dissipation time, the accretion of matter by the forming protoplanets and the protoplanets migration times, to allow for a correct prediction of observed planets mass distributions. The main known features of disc-planet interactions, derived from analytical studies (Artymowicz 1993; Goldreich & Tremaine 1979, 1980; Papaloizou & Lin 1984; Lin & Papaloizou 1986a,b), and from numerical simulations (D'Angelo et al. 2003b, and references therein), can be summarized as follows: 1) the existence of Lindblad resonances in the accretion disc; 2) the action of gravitational torques on the planet's orbit, causing planet migration; 3) the possible formation of a density gap in the region of a planet's orbit, depending on planet's mass; 4) the existence of two main migration mechanism: type I in which the planet is embedded in the disc and type II in which the planet is located inside the disc gap (Ward 1997) depending

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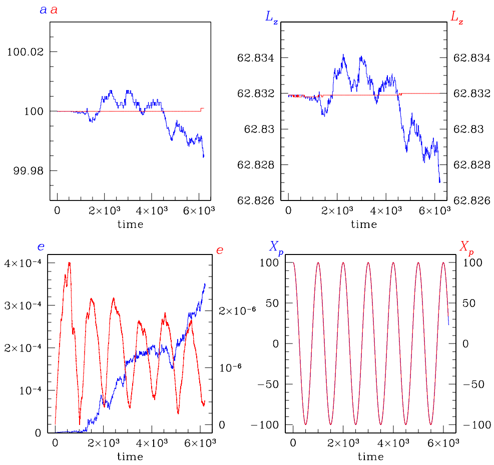

Fig. 1. Planet orbital parameters evolution with Keplerian accretion discs (see text).

on the absence or presence of the density gap. Type I migration should be dominated by gravitational torques, while type II should follow a viscosity driven migration. While the accretion times for planets seem to be of 1 – 10 Myr on the grounds of observational constrains from T-Tauri stars (Hartmann 2000), migration times of the order of 10^4 – 10^5 years, starting from about 5 AU are currently predicted and the observational discovery of many Jupiter-like planets below 3 AU suggests that migration mechanisms carrying planets towards the central star are actually in action, but a clear and totally self-consistent "picture" of the overall process is still lacking. Anyway, models still suffer from many uncertainties: most models in literature have been built using hypotheses like laminar disc motion and Keplerian distribution of gas velocity, while turbulence is believed to play a role in planet migration, and a detailed study on this matter is still needed (Nelson & Papaloizou 2004, and references therein); estimates of disc mass and accretion rates based on infrared irradiation measurements from the accretion disc are often based on some simplified assumptions concerning opacity and disc physical and chemical composition (Hartmann 2000); uncertainties are present in the effectiveness of migration mechanisms like Lindblad resonances torques or co-rotational torques (Artymowicz 2004).

In order to help exploring the contribution of planet-disc interactions on planet migration mechanisms, we present here a study on the evolution of a single planet orbit embedded in an accretion disc with sub-Keplerian initial velocity for gas particles, with the use of a Lagrangian Smoothed Particle Hydrodynamic code, as other calculations present in the literature are mostly based on grid models (see Schäfer et al. 2004, for an SPH based study). Evaluation of migration times, orbital parameters evolution and their dependence on planet mass and initial angular momentum of gas particles are focused here.

2. The model

The simulations presented in this work are based on the SPH method (Monaghan 1992). The code does not contain a specific radiation treatment, but the used equation of state: $P = (\gamma - 1)\rho u$, where u is the thermal energy per unit mass, includes the polytropic index γ, which can be adjusted to values lower than 5/3 if radiation, partial molecular dissociation or partial ionisation effects are present, giving the overall effect of a higher compressibility to the gas. Current calculations are performed with the simple choice of $\gamma = 5/3$, but we intend to further investigate this matter in a future work.

The model is two-dimensional and it is built in Cartesian coordinates with dimensionless quantities. Reference physical units are: 1) the initial stellar mass M_0; 2) the stellar radius R_0; 3) the Keplerian orbital period of an orbit of radius R_0 around a star of mass M_0.

The initial structure of our disc has an axial symmetry, as the accretion disc is created through the injection of particles at point-like positions (injectors) along circles concentric with the central star. Particles have an initial tangential velocities set by choosing a value for the angular momentum per unit mass λ. Three choices are made here for λ: 18, 36, 54 with particles injected at a radial distance of 130. All the three choices give a sub-Keplerian feature to the velocity distribution of the accretion disc (particles injected at a radial distance of 130, would have Keplerian velocity with $\lambda \sim 70$), so that injected particles start decreasing their distance to the centre, until they "hit" the centrifugal barrier. The accretion disc reaches a nearly steady state population of particles (equilibrium between injected particles and particles captured by the central star) with $2 \times 10^5 - 5 \times 10^6$ particles, depending on the model, when using a smoothing length (spatial resolution parameter) $h = 0.3$. At this stage, the planet is inserted and the model is evolved considering the following interactions:

1. gravitational interaction between gas particles and central star;
2. gravitational interaction between planet and star;
3. gravitational interaction between particles and planet;
4. gas pressure between neighbouring gas particles;
5. artificial viscosity (pressure contribution) between gas particles;
6. gas particle capture by the planet when gas particles approach the planet area (conservation of momentum is used to correct the planet speed before removing the particle).

No self-gravitation is included in the gas for computational reasons, and given the masses used for the particles (see below) this is not believed to be too rough an approximation. Currently no physical viscous terms are included in the equation, as our aim is currently to explore gravitational effects due to disc non axisymmetric evolution and gas accretion effects onto the planet, but there are plans to include physical viscosity in a future work, in order to better explore the viscosity driven migrations (like in type II migration models) and viscosity contribution in general.

The computational domain is circular, extended in the xy plane with a radius of 150 (the star is located in the "origin"), and the planet is located inside the disc plane, with the initial position at $X_p = 100$ and $Y_p = 0$. 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 $10^{-6} - 10^{-5}$. Calculations are performed with two masses for the planet: 10^{-7} (earth-like planet) and 10^{-3} (Jupiter-like planet).

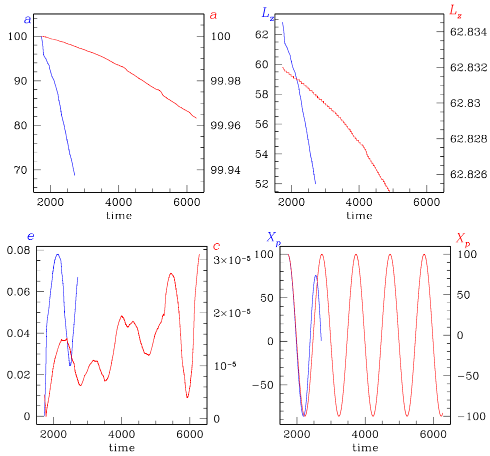

Fig. 2. Planet orbital parameters evolution with the $\lambda = 18$ accretion discs (see text).

For comparison purposes, two models (one with an earth-like planet and the other with a Jupiter-like planet) are built using an initial exactly Keplerian distribution of gas particle velocities, with an initial uniform density over the entire disc area.

3. Preliminary results

Most of our calculations are still under development at the time of this writing, but some preliminary results are presented here. Figures 1-4 show the evolution of the planet orbital parameters for the set of performed calculations. Each figure shows the semi-major axis a, the eccentricity e, the planet angular momentum per units mass L_z and the X_p planet coordinate, as a function of time. Blue lines give the results for the earth-like planet, while red lines give Jupiter-like planet results. Fig. 1 includes results for the accretion disc with initial Keplerian velocity distribution, while other figures show results for sub-Keplerian models with gas particles initial angular momentum $\lambda = 18, 36, 54$ respectively.

Our calculations are still limited to a few planet orbits, as it can be evinced from X_p periodic variation. In the case of Keplerian discs,

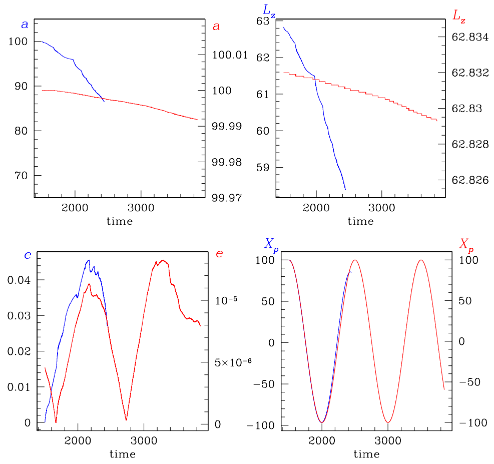

Fig. 3. Planet orbital parameters evolution with the $\lambda = 36$ accretion discs (see text).

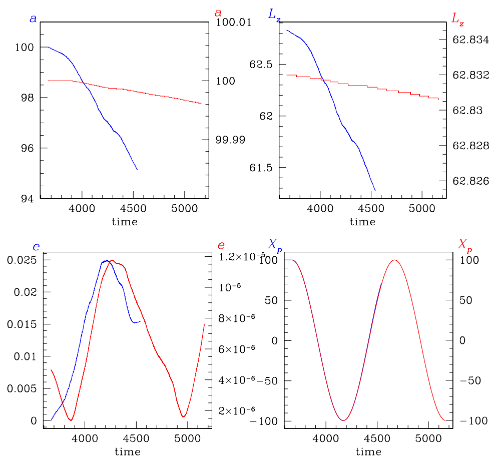

Fig. 4. Planet orbital parameters evolution with the $\lambda = 54$ accretion discs (see text).

not much can be said about the timeline of a possible non-periodic evolution of the orbital parameters for the Jupiter-like planet, while a decrease of about 0.01% in the semi-major axis in 6 orbits is visible for the earth-like planet, which would bring down the planet onto the central star in about $10^5 - 10^6$ orbits. A non periodic evolution of the orbital parameters is already visible in the sub-Keplerian discs, probably due to capture of "falling" gas particles by the planet. Due to different planet/particle mass ratio, the lifetime of this evolution is noticeably faster for the earth-like planet, with a lowering rate of the semi-major axis a of 30%, 10% and 5% in about one planet orbit for $\lambda = 18, 36, 54$ respectively, while changes for the Jupiter-like planet are much slower, with a maximum variation of a of 0.01% in one orbit for the $\lambda = 18$ case.

Concerning the eccentricity, all our models start with zero ($\sim 10^{-6}$) eccentricity, and the following evolution shows an enhancement effect for some models (Keplerian disc with earth-like planet), a nearly periodic behaviour (most sub-Keplerian models) or an irregular behaviour (model with $\lambda = 18$ and Jupiter-like planet). We need to evolve our models further to state clearer conclusions from our analysis.

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