SF2A 2011
G. Alecian, K. Belkacem, R. Samadi and D. Valls-Gabaud (eds)

PLANETS FORMED BY GRAVITATIONAL INSTABILITY SHOULD RAPIDLY MIGRATE INWARD

C. Baruteau[1], F. Meru[2] and S.-J. Paardekooper[1]

Abstract. The observation of massive exoplanets at large orbital separation from their host star challenges theories of planetary formation. A possible formation mechanism involves the fragmentation of massive protoplanetary discs into clumps. While the conditions for fragmentation have been extensively investigated, little is known of the subsequent evolution of these giant planet embryos, in particular their expected orbital migration. We examine in this communication the interaction between a single planet and the gravitoturbulent disc it is embedded in, following the assumption that the planet has formed by gravitational instability. We show that such planets should rapidly migrate towards the inner parts of protoplanetary discs, regardless of the planet mass.

Keywords: accretion, accretion discs, turbulence, methods: numerical, planetary systems: formation, planetary systems: protoplanetary discs

1 Introduction

Planets observed a few tens of au away from their host star are thought to be potential candidates for the formation scenario based on the gravitational instability (GI) of massive protoplanetary discs. A few numerical studies have observed that clumps could drift inwards (e.g., Mayer et al. 2002), some of them having focused on the early phases of disc formation and evolution following the collapse from the prestellar core stage (e.g., Machida et al. 2011). In a recent paper (Baruteau et al. 2011), we have shown that the interaction between a planet and the fully gravitoturbulent disc it is embedded in leads to the rapid inward migration of the planet. Our model and results of simulations are summarized below.

2 Physical model

We investigate the tidal interaction between a massive planet and the protoplanetary disc it formed in through the GI scenario. Two-dimensional hydrodynamical simulations were carried out for this purpose. Our study does not address the formation of the planet after the fragmentation stage. We consider instead an already formed single planet embedded in its nascent gravitoturbulent disc. We first set up a quasi steady-state disc, in which shock heating arising from the gravitoturbulence, modeled with a von Neumann-Richtmyer artificial bulk viscosity, is balanced by cooling. A simple but common prescription is used for the disc cooling, where the ratio of the cooling timescale to orbital period is taken to be a constant, denoted by β. Since we require the disc to be in a gravitoturbulent state, but we do not require fragmentation, we simulated various disc models with $\beta \geq 15$. In the following, results are shown for $\beta = 30$.

3 Results of simulations

Before inserting the planet, our model comprises an $\approx 0.25 M_{\odot}$ disc around a star of fixed mass $M_{\star} = M_{\odot}$, spanning a radial range $20 < r < 250$ au. The radial profile of the surface density is ≈ 15 g cm^{-2} $(r/100\,\mathrm{au})^{-3/2}$, and that of the temperature ≈ 10 K throughout the disc. The time-averaged radial profile of the alpha viscous

---

[1] DAMTP, University of Cambridge, Wilberforce Road, Cambridge CB30WA, United Kingdom
[2] Institut für Astronomie und Astrophysik, Universität Tübingen, Auf der Morgenstelle 10, 72076 Tübingen, Germany

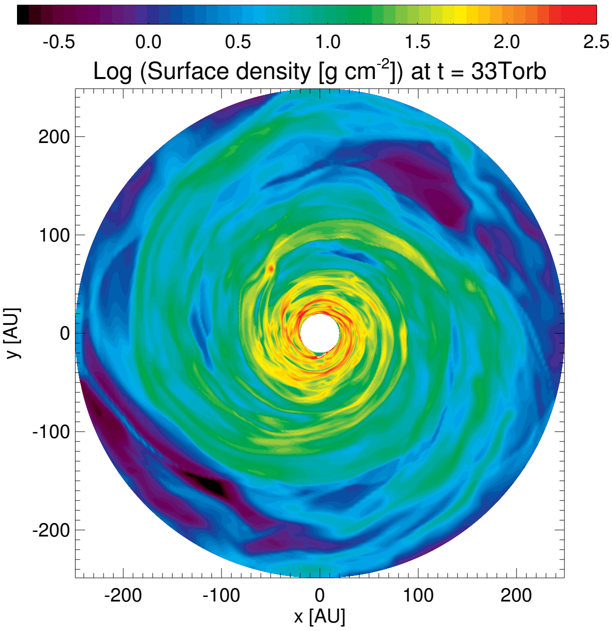

Fig. 1. Disc's surface density obtained in a restart simulation with $\beta = 30$, where a Jupiter-mass planet has been introduced at 100 au. Results are displayed three orbits after the restart time. The planet is now located at about 80 au from the central star (at $x \sim -50$ au, $y \sim 60$ au).

parameter associated with gravitoturbulence, $\langle\alpha\rangle$, is also approximately uniform ($\langle\alpha\rangle \approx 2.5\%$). The above density and temperature profiles result from the fact the disc reaches a quasi steady-state with uniform profiles of its Toomre-Q and $\langle\alpha\rangle$ parameters.

Simulations were restarted with including a single planet at 100 au. We considered three planet masses about the typical initial mass of a clump formed by GI (Boley et al. 2010): a Saturn-mass planet, a Jupiter-mass planet and 5 Jupiter-mass planet (for more details, see Baruteau et al. 2011). For each planet mass, a series of eight runs was performed with varying the planet's azimuth at restart. Fig. 1 displays the gas surface density in one of the restart runs with the Jupiter-mass planet, and we see that the density perturbation due to the planet is comparable to the turbulent density perturbations.

The time evolution of the planets orbital separation is depicted in Fig. 2. The net trend coming out of our results is that planets migrate inwards very rapidly, despite the stochastic kicks due to gravitoturbulence. The averaged migration timescale is typically shorter than 10^4 years, regardless of the planet mass. Smaller planets are more sensitive to stochastic kicks, but also migrate inwards very fast. Stochastic kicks may be directed inwards or outwards depending on the density turbulent fluctuations inside the planet's horseshoe region. They can be seen as an effective, *temporary* type III migration feature coming on top of the inward migration due to the background disc–planet tidal torque.

Because their formation and migration timescales are shorter than their gap-opening timescale (partly because of the disc's vigorous turbulence), planets do not have time to open a dip or a gap around their orbit in our model. They are therefore not subject to the type II and *runaway* type III migration regimes. The comparison of our results with those of equivalent laminar disc models shows that the averaged torque driving the net inward migration in gravitoturbulent discs is actually very similar to the one leading to type I migration in the absence of turbulence. We interpret the rapid inward migration in our model as due to an increasing radial profile of the disc entropy in a steady state, which yields a large negative horseshoe drag adding up to the negative differential Lindblad torque. We argue that in discs with uniform Toomre-Q profiles and cooling-to-orbital timescale ratios, rapid inward migration should be a generic expectation for planets formed by GI.

4 Concluding remarks

We have shown that massive planets formed at large separation from their star by GI are unlikely to stay in place, and should rapidly migrate towards the inner parts of protoplanetary discs, regardless of the planet mass.

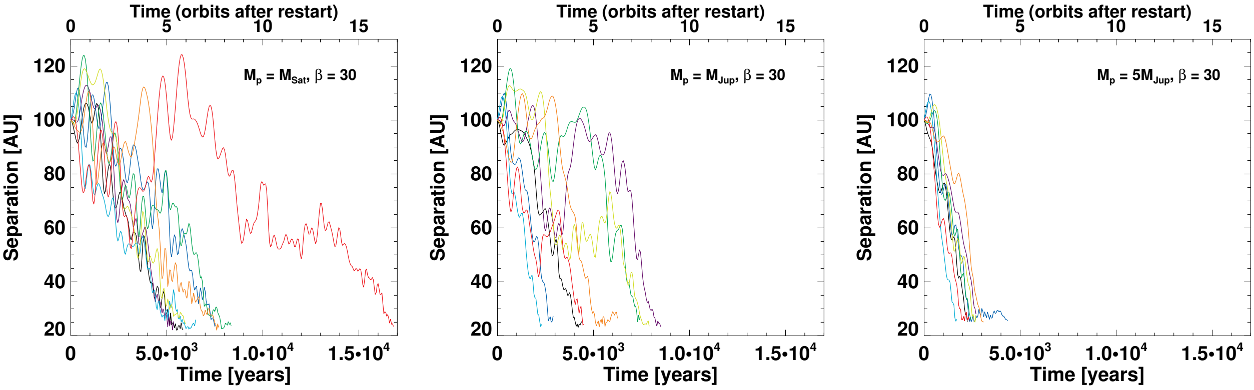

Fig. 2. Time evolution of the orbital separation of a Saturn-mass planet (left column), a Jupiter-mass planet (middle column), and a 5 Jupiter-mass planet (right column) in a gravitoturbulent disc with $\beta = 30$. Time is displayed in years (bottom x-axis), and in orbital periods at 100 au (top x-axis). Results are obtained for eight evenly-spaced planet's azimuths at restart.

Such planets are not necessarily to reach the very vicinity of their host star. The inner parts of protoplanetary discs should indeed be too hot to be gravitationally unstable, and other sources of turbulence, such as the magnetorotational instability, could prevail, changing the background disc profiles as well as the amount of turbulence. It is thus possible that the rapid type I migration of planets formed by GI slows down in the disc inner parts and results in the formation of a gap. Although the formation of several planets by GI and their mutual interactions could change the above picture, we speculate that the planets in the HR 8799 system (Marois et al. 2010) could have formed by GI, if the fastest migrating planet slows down or stalls its migration in the disc inner parts, and that the (possibly sequential) convergent migration of the outer planets leads to their capture into mean-motion resonance.

References

Baruteau, C., Meru, F., & Paardekooper, S.-J. 2011, MNRAS, 416, 1971
Boley, A. C., Hayfield, T., Mayer, L., & Durisen, R. H. 2010, Icarus, 207, 509
Machida, M. N., Inutsuka, S., & Matsumoto, T. 2011, ApJ, 729, 42
Marois, C., Zuckerman, B., Konopacky, Q. M., Macintosh, B., & Barman, T. 2010, Nature, 468, 1080
Mayer, L., Quinn, T., Wadsley, J., & Stadel, J. 2002, Science, 298, 1756