EPSC Abstracts
Vol. 8, EPSC2013-209, 2013
European Planetary Science Congress 2013

Orbital Migration of Protoplanets in a Marginally Gravitationally Unstable Disk

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Abstract

Core accretion and disk instability require giant protoplanets to form in the presence of disk gas. Protoplanet migration models generally assume disk masses low enough that the disk's self-gravity can be neglected. However, disk instability requires a disk massive enough to be marginally gravitationally unstable (MGU). Even for core accretion, a FU Orionis outburst may require a brief MGU disk phase. We present a new set [1] of three dimensional, gravitational radiation hydrodynamics models of MGU disks with multiple protoplanets, which interact gravitationally with the disk and with each other, including disk gas mass accretion. Initial protoplanet masses are 0.01 to 10 $M_\oplus$ for core accretion models, and 0.1 to 3 M_{Jup} for Nice scenario models, starting on circular orbits with radii of 6, 8, 10, or 12 AU, inside a 0.091 $M_\odot$ disk extending from 4 to 20 AU around a $1 M_\odot$ protostar. Evolutions are followed for up to $\sim$ 4000 yr and involve phases of relative stability ($e \sim 0.1$) interspersed with chaotic phases ($e \sim 0.4$) of orbital interchanges. The 0.01 to 10 $M_\oplus$ cores can orbit stably for $\sim$ 1000 yr: monotonic inward or outward orbital migration of the type seen in low mass disks does not occur. A system with giant planet masses similar to our Solar System (1.0, 0.33, 0.1, 0.1 M_{Jup}) was stable for over 1000 yr, and a Jupiter-Saturn-like system was stable for over 3800 yr, implying that our giant planets might well survive a MGU disk phase.

1. Introduction

The discovery of short-period giant planets forced theorists to study inward orbital migration of giant planets formed at much greater distances. Attention has focused on Type I and Type II migration [2], the former dealing with $\sim 10 M_\oplus$ cores that migrate rapidly due to tidal torques with the gaseous disk, and the latter dealing with $\sim M_{Jup}$ protoplanets that are massive enough to open a gap in the disk, and thereafter evolve along with the disk. Unchecked inward Type I migration presumably can lead to a loss of the protoplanet. Most Type I migration models consider disks with masses low enough that the disk's self-gravity can be ignored. Disk instability scenarios for giant planet formation in self-gravitating disks may sidestep the danger of Type I migration, as the clumps initially formed have masses of order 1 M_{Jup} (e.g., [3]), large enough to open disk gaps and undergo Type II migration in a low mass disk.

The Nice model has become a leading explanation for the orbital evolution of the giant planets in our solar system [4]. While the Nice model was derived in the context of the core accretion model for giant planet formation, the question arises as to the orbital stability of multiple giant planet systems during a MGU phase, such as during a FU Orionis outburst prior to gaseous disk dissipation in the core accretion scenario, or as a result of formation by the disk instability mechanism.

Previous work [3] studied the orbital evolution of single "virtual protoplanets" (VP) with initial masses of 1 M_{Jup} embedded in a MGU disk. Here we present two new set of models, each with up to four VPs initially present in the MGU disk. In the first set, the VP masses are chosen to investigate the orbital evolution of $\sim$ Earth-mass cores trying to accrete gas during an MGU disk phase, and in the second set, to investigate the evolution of already formed giant planets embedded in MGU disks, a situation analogous to the Nice model of giant planet evolution in gas-free, massive planetesimal disks.

2. Results and Summary

Figure 1 shows the midplane of the MGU disk when the planets are inserted [1], while Figure 2 shows the evolution of four models based on a Nice-like scenario for a MGU disk [1].

As previously found [3], protoplanets located at $\sim$ 10 AU in a MGU disk can orbit relatively stably for significant periods of time ($\sim 10^3$ yr or more), without undergoing monotonic inward Type-I-like migration, and without opening a disk gap, leading to Type-II-like migration. Instead, the quasi-periodic gravi-

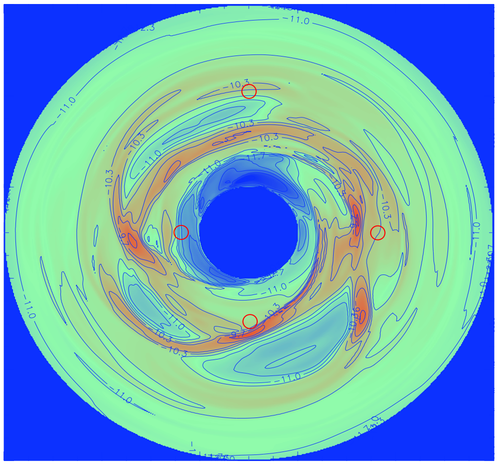

Figure 1: Midplane density contours for the MGU disk at the phase when the protoplanets (red circles) are first inserted into the models [1]. Red circles denote the locations where protoplanets are inserted.

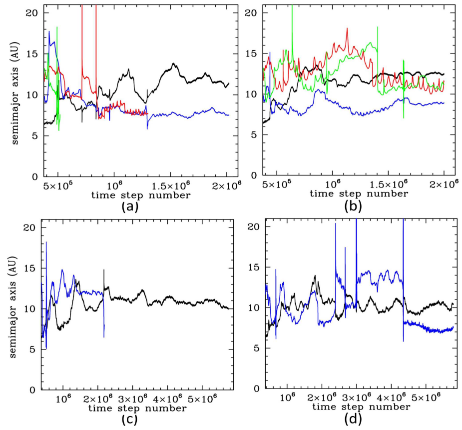

Figure 2: Time evolution of the semimajor axes of protoplanets in a Nice-like scenario, with initial masses ranging from 0.1 to 1 M_{Jup}. Elapsed times: (a) and (b): 1200 yr, (c) and (d): 3800 yr. Protoplanets that strike the inner (4 AU) or outer (20 AU) disk boundaries are considered to be ejected and disappear from the plots.

tational perturbations induced by the spiral arms and clumps of the MGU disk result in eccentric orbits ($e \sim 0.2$), while close encounters with the other protoplanets, combined with the MGU disk interactions, can lead to a significant number of "ejections" of the less massive protoplanets through hitting the inner or outer disk boundaries, though these "ejections" might very well be ameliorated in models that included a disk that extended from the true surface of the protostar ($\sim$ 0.05 AU) out to much larger distances ($\sim$ 50 AU).

The models illustrate the range of outcomes that could result from a MGU disk phase during planetary system formation. A MGU disk phase need not be fatal to growing cores in the core accretion scenario, or to giant planets formed by either core accretion or disk instability, at least not for protoplanets with initial orbits in the range of 6 AU to 12 AU from a solar-mass protostar. It is even conceivable that a Nice model-like scenario could be constructed for protoplanets that survive a MGU disk phase, though the most Nice-like model presented here ended up with Jupiter as the outermost body, rather than the innermost. Other initial conditions might well lead to a more Nice-like outcome.

Acknowledgements

This research was supported in part by the NASA Origins of Solar Systems Program (NNX09AF62G) and contributed in part to the NASA Astrobiology Institute (NNA09DA81A).

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