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Inward-then-outward migration of Jupiter and Saturn and its implications for Uranus and Neptune

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Abstract

Jupiter and Saturn formed in the gaseous Solar Nebula and were subject to gas-driven migration. The "Grand Tack" model of Walsh et al. (2011) proposes that Jupiter and Saturn underwent a two phase, inward-then-outward migration that sculpted the inner Solar System. We use hydrodynamical simulations to investigate how Jupiter and Saturn's orbital history depends on both the giant planets' accretion history and the disk properties (viscosity, density, radiative properties). We show that a two phase migration of Jupiter and Saturn is a robust outcome that is independent of the growth history of these planets, and fits coherently within the framework of an evolving Solar Nebula. We then test the impact on the growth of Uranus and Neptune. For some system parameters the ice giants undergo a rapid burst of accretion during the short outward migration phase of Jupiter and Saturn. We also find that co-orbital configurations are common between the ice giants (or sometimes between an ice giant and a gas giant).

1. Introduction

For over 20 years, simulations of terrestrial accretion have been unable to reproduce Mars' relatively small mass of $0.11 M_\oplus$ (e.g. [4]). Such a problem arises because in standard disk models, too much mass lies in Mars's vicinity. To solve this problem, Walsh et al. [5] proposed that this mass is removed as a consequence of the radial migration of Jupiter and Saturn. In this model, Jupiter migrated inward, then "tacked" and migrated outward when Saturn was captured in 3:2 resonance, in agreement with hydrodynamical simulations ([2]). If Jupiter's tack occurred at ~ 1.5 AU then it naturally truncates the inner disk of planetesimals and embryos at 1 AU and a small Mars forms (e.g., [1]).

Here we use hydrodynamical simulations to test the dependence of this two-phase migration of Jupiter and Saturn on the accretion and orbital history of these planets and on the disk properties. We then present the results of both hydrodynamical and N-body simulations which study the effect of Jupiter's tack on the formation of the outer Solar System and on the growth of the icy giants.

2. Two phase migration of Jupiter and Saturn

In the simulations, Jupiter and Saturn start as 10 $M_\oplus$ cores and grow by accreting gas from the disk. We considered different scenarios for the mass-growth history of the planets and tested the effect of varying the disk viscosity, surface density, and equation of state (including fully radiative disks).

In most cases, Jupiter and Saturn's core are initially captured in 3:2 mean motion resonance (MMR). When Jupiter starts to accrete gas, the resonance is broken and the planets move apart. When Saturn reaches the gap-opening mass, its inward migration accelerates and it catches back up to Jupiter and is once again caught in the 3:2 MMR. Outward migration of both giant planets is then triggered via the mechanism of Masset & Snellgrove [2] and terminates when the disk dissipates. Fig. 1 illustrates the evolution of the system for a simulation in which Saturn started to accrete gas when Jupiter reached half of its final mass.

Jupiter's "tack" and the outward migration rate of Jupiter and Saturn are nearly independent of the accretion and orbital history but do depend somewhat on the disk parameters (e.g., the aspect ratio), surface density profile, and equation of state [3].

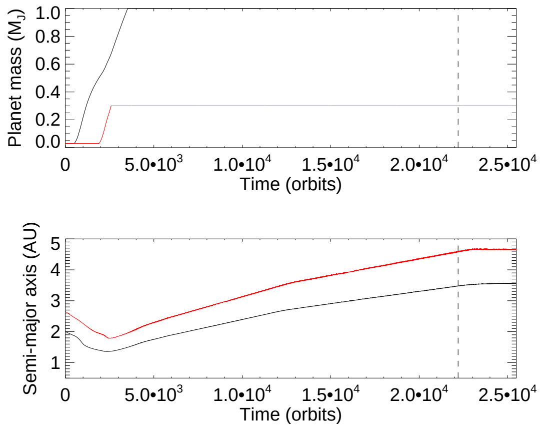

Figure 1: Evolution of Jupiter's and Saturn's masses and semi-major axes for a simulation in which Saturn starts to accrete gas when Jupiter reaches half of its full mass. The vertical dashed line marks the start of the dispersal of the gas disk.

3 Effect on the formation of the outer Solar System

As Jupiter and Saturn migrate outward, the region from 5-12 AU is strongly compressed by gravitational effects, which should act to promote collisions between protoplanets and to accelerate Uranus and Neptune's growth. To investigate this issue, we performed simulations of the growth of Uranus and Neptune from embryos of a few $M_\oplus$ during the outward migration of Jupiter and Saturn. We used both hydro simulations to self-consistently model the outward migration of Jupiter and N-body simulations that sometimes include a population of planetesimals. Fig. 2 shows the results of a N-body simulation that started with Jupiter and Saturn migrating outward plus 6 cores of $8.33\ M_\oplus$ between 5 and 15 AU. Outward migration of Jupiter and Saturn compresses the system of protoplanets, which favors collisions between them. For this simulation, the final state of the system of embryos consists of two co-orbitals with masses 16.6 and 25 $M_\oplus$ at 9.4 AU plus a 8.3 $M_\oplus$ planet at 14.5 AU.

4. Summary and Conclusions

The Grand Tack scenario is supported by hydrodynamical simulations that suggest that Jupiter and Saturn's outward migration is a robust outcome, independent of the accretion and orbital history of the planets.

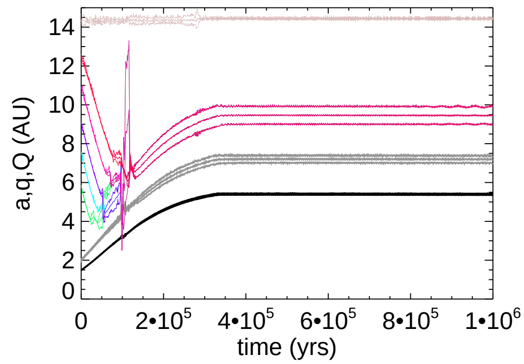

Figure 2: Orbital evolution (semimajor axis, ap- and peri-helion distances) of a system composed of Jupiter and Saturn migrating outward plus six $8.3\ M_\oplus$ protoplanets located between 5 and 15 AU. The final state consists of two co-orbital planets of masses 16.6 and $25\ M_\oplus$ at 9 AU plus one $8.3\ M_\oplus$ planet at 14.5 AU.

The Grand Tack can play an important role on the dynamics and accretion of Uranus and Neptune because the system of protoplanets which formed in the outer disk tends to be compressed, which promotes collisions between embryos and favors the formation of trojan planets.

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