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Growth of Jupiter: Enhancement of core accretion by a voluminous low-mass envelope

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ABSTRACT

We present calculations of the early stages of the formation of Jupiter via core nucleated accretion and gas capture. The core begins as a seed body of about 350 km in radius and orbits in a swarm of planetesimals whose initial radii range from 15 m to 50 km. The evolution of the swarm accounts for growth and fragmentation, viscous and gravitational stirring, and for drag-assisted migration and velocity damping. During this evolution, less than 9% of the mass is in planetesimals smaller than 1 km in radius; $\lesssim$25% is in planetesimals with radii between 1 and 10 km; and $\lesssim$7% is in bodies with radii larger than 100 km. Gas capture by the core substantially enhances the size-dependent cross-section of the planet for accretion of planetesimals. The calculation of dust opacity in the planet's envelope accounts for coagulation and sedimentation of dust particles released as planetesimals are ablated. The calculation is carried out at an orbital semi-major axis of 5.2 AU and the initial solids' surface density is 10 g cm^{-2} at that distance. The results give a core mass of nearly 7.3 Earth masses ($M_\oplus$) and an envelope mass of $\approx$0.15 $M_\oplus$ after about 4×10^5 years, at which point the envelope growth rate surpasses that of the core. The same calculation without the envelope yields a core of only about 4.4 $M_\oplus$.

1. Introduction

The formation of Jupiter is a key element in the classical problem of the origin of the Solar System. Detailed studies of the formation of this planet by core-nucleated accretion have been carried out for decades (Safronov, 1972; Perri and Cameron, 1974; Mizuno, 1980; Bodenheimer and Pollack, 1986; Pollack et al., 1996). The latter work studied what is now considered to be a standard case: the formation of Jupiter, in a fixed orbit at 5.2 AU, in a disk with solid surface density $\sigma_Z = 10\,\mathrm{g\,cm^{-2}}$, about three times as high as that in the minimum-mass solar nebula (Weidenschilling, 1977; Hayashi, 1981). Pollack et al. (1996)'s basic conclusion was that the formation time can range from 1.25 to 8 Myr, depending on physical assumptions made in the computations. The heavy-element core masses fell in the range 12–20 Earth masses ($M_\oplus$).

Jupiter's growth involves numerous elements of physics over a wide range of mass and length scales. The initial steps in the process involve the buildup of planetesimals from an initial distribution of sub-micron-size dust grains (e.g., Chiang and Youdin, 2010). The work described in the present paper starts at a somewhat later stage, when a swarm of planetesimals, with radii ranging from several meters to tens of kilometers, has formed, along with a nascent planetary embryo of somewhat larger size. The embryo (composed almost entirely of elements heavier than hydrogen and helium) builds up by accretion of planetesimals and becomes the planetary core. When its mass reaches $\sim$0.1 $M_\oplus$, and when the escape speed from its surface exceeds the thermal speed of molecules in the surrounding gas disk, it begins to capture a small amount of gas. This gas is assumed to have nearly solar composition. However, the accretion rate of solids onto the core ($\dot{M}_c$) greatly exceeds, for some time, the accretion rate of gas ($\dot{M}_e$, composed primarily of molecular hydrogen and helium). Once the core has accreted most of the planetesimals within its gravitational reach, $\dot{M}_c$ slows down significantly and $\dot{M}_e$, which is increasing, begins to exceed it. Thereafter, during a phase characterized by slow gas accretion, M_c continues to grow, but less rapidly than M_e, until the *crossover mass* is reached ($M_c = M_e$). We denote by "Phase

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1" the time up to the point where $\dot{M}_e = \dot{M}_c$, and by "Phase 2" the time from there up to crossover. At or before crossover, the rapid gas accretion phase begins ($\dot{M}_e \gg \dot{M}_c$). The gas accretion rate is at first limited by the rate at which the envelope can contract and release energy, governed primarily by the opacity due to dust and gas. The contraction rate increases and soon reaches the point where the accretion rate required by the contraction exceeds the rate at which the disk can provide gas. The *disk-limited* accretion phase begins, with the gas accretion rate depending on several factors: planet mass, planet orbital radius, disk gaseous density, disk kinematic viscosity, and disk scale height. The total planet mass (M_p) at which the disk-limited phase starts is typically several tens of Earth masses (Lissauer et al., 2009). Disk-limited accretion rates are determined by three-dimensional hydrodynamics simulations of a planet embedded in a disk (Lissauer et al., 2009; Bodenheimer et al., 2013, and references therein). The final mass of the planet is determined by a combination of gap opening, which drastically reduces accretion, and the dissipation of the nebular gas.

In the case of Jupiter, there are several observational constraints that must be satisfied by any formation model. Protoplanetary disk lifetimes have a median value of ~3 Myr and a maximum of ~10 Myr (Hillenbrand, 2008; Roberge and Kamp, 2011). The mass ($M_\mathrm{J} = 1.898 \times 10^{30}$ g), equatorial radius ($R_\mathrm{J} = 7.15 \times 10^9$ cm) and gravitational moments J_2, J_4, J_6 are measured, constraining the mean density and density distribution. The Galileo probe measured the abundances of a number of elements in Jupiter's outer layers (Young et al., 1996; Owen et al., 1999; Young, 2003) and determined that they were in the range of 2–4 times solar. Derived core masses from models of the interior of Jupiter vary considerably depending on the equation of state and assumed composition layering. Militzer et al. (2008) obtain $M_c = 16 \pm 2\ \mathrm{M}_\oplus$; Nettelmann et al. (2012) find $M_c = 0$–$8\ \mathrm{M}_\oplus$; Saumon and Guillot (2004) find $M_c = 0$–$11\ \mathrm{M}_\oplus$. The Nettelmann three-layer models are consistent with the abundances measured by Galileo in the atmosphere, and have total heavy-element masses in the range 28—32 $\mathrm{M}_\oplus$, about six times solar. However, this quantity is not well constrained. Estimates range from 0 to 18 $\mathrm{M}_\oplus$ for the core mass M_c, and from 15 to 40 $\mathrm{M}_\oplus$ for the total heavy-element mass M_Z (Fortney and Nettelmann, 2010). In this paper, we do not distinguish between the two masses M_c and M_Z.

Several major improvements in the physical basis of the computations have been made since the work of Pollack et al. (1996). Alibert et al. (2005) and Mordasini et al. (2012) include the effects of disk evolution and planetary orbital migration on the formation process. Lissauer et al. (2009) and Bodenheimer et al. (2013) use gas accretion rates for the disk-limited phase based on three-dimensional hydrodynamic simulations of disk flow around an embedded planet. Movshovitz et al. (2010, hereafter MBPL10) calculate the dust opacity in the envelope of the forming planet self-consistently by including the effects of dust settling and coagulation. The results of MBPL10 show a significant increase in gas accretion rate prior to the disk-limited phase, due to the reduced opacity (and hence faster cooling) in the outer parts of the planet's envelope. Inaba et al. (2003) include a statistical treatment of the planetesimal accretion rate onto the core, an improvement over the more approximate treatment of this rate by Pollack et al. (1996). The time to form the initial core is crucial in determining the formation time for the entire planet. They include the enhancement in the capture cross-section for planetesimals as a result of the presence of the gaseous envelope, as well as collisional fragmentation of planetesimals and a range of planetesimal sizes. Inaba et al. (2003) came to the basic conclusion that a very high surface density of solid material in the initial disk, $\sigma_Z = 25\ \mathrm{g\ cm^{-2}}$ at 5.2 AU, was required to build a core of 21 $\mathrm{M}_\oplus$ within the lifetime of the protoplanetary disk. This core mass is above the values required to initiate rapid gas accretion (which they did not calculate) but their σ_Z implies a disk mass well above typical observed values. The above result was obtained with assumed interstellar grain opacities in the planet's atmosphere. If these opacities are reduced by a factor 100, they find that with a smaller value of the surface density, $\sigma_Z = 12.5\ \mathrm{g\ cm^{-2}}$, a core of 7 $\mathrm{M}_\oplus$ can form at 5.2 AU in 5 Myr, probably sufficient to collect gas.

The results of Inaba et al. (2003) imply that core formation times at 5.2 AU are actually longer than those calculated by, for example, Pollack et al. (1996) with an assumed $\sigma_Z = 10\ \mathrm{g\ cm^{-2}}$. Inaba et al. (2003) also confirm the findings of Pollack et al. (1996) that the grain opacity is an important quantity during initial core formation. If the opacity is reduced, the envelope density must increase to maintain hydrostatic and thermal equilibrium during Phase 1, at a given core accretion rate; thus, more gas flows into the envelope and the capture cross-section for planetesimals is enhanced.

In this paper we consider the initial core formation, Phase 1, at 5.2 AU with $\sigma_Z = 10\ \mathrm{g\ cm^{-2}}$, a reasonable value for an initial solar nebula (Weidenschilling, 2005). The main question to be answered is whether or not a core of 5—10 $\mathrm{M}_\oplus$ can be formed on a timescale of less than $1-2$ Myr. An initial core (at the end of Phase 1) in that mass range is likely to accrete gas and build up to a Jupiter mass in less than a typical disk lifetime (MBPL10). To answer that question we combine two state-of-the-art codes, one for the statistical treatment of planetesimal accretion, and the other for the calculation of the structure, evolution, and capture cross-sections of the planet's gaseous envelope. The grain opacity in the envelope includes the effects of coagulation and settling. The two codes interact, in that the planetesimal code provides $\dot{M}_c$ while the envelope code provides M_e and the capture radius for each planetesimal size in the assumed range. The details of the codes are presented in Section 2. Previous relevant studies and some of their findings are briefly reviewed in Section 3. Our results are discussed in Section 4, and compared with parallel calculations (i) without the presence of the envelope, and (ii) with the envelope but with the core accretion rates used in previous works including Pollack et al. (1996) and MBPL10. The conclusions are presented in Section 5.

2. Numerical procedures

In this section, we outline the main numerical procedures that are employed in our models of Jupiter's core accumulation and envelope formation.

2.1. The planetesimal accretion code

A detailed discussion of the solid-body accretion code is presented in Weidenschilling et al. (1997, see also Weidenschilling, 2011). Here we present a general summary of the method and the procedure as used in the simulations. The accretion code computes collisional and gravitational interactions within a swarm of planetesimals extending over a wide range of heliocentric distances. The swarm is divided into a number of radial zones, each corresponding to a narrow range of semi-major axes. Within each of these zones, the size–frequency distribution is represented by the number of bodies in each of a series of logarithmic diameter bins, chosen so that the mean mass differs by a factor of two between adjacent bins. Each bin has mean values of orbital eccentricity and inclination, with an assumed range about the mean. During a time-step, all zone/bin combinations that have crossing orbits are identified. Impact probabilities are computed, based on the relative velocities, gravitationally enhanced collisional cross-sections, and the fractional overlap of orbits. Based on these probabilities, the locations of a set of typical collisions are selected