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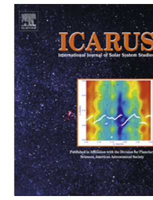

Giant planet formation with pebble accretion

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ABSTRACT

In the core accretion model for giant planet formation, a solid core forms by coagulation of dust grains in a protoplanetary disk and then accretes gas from the disk when the core reaches a critical mass. Both stages must be completed in a few million years before the disk gas disperses. The slowest stage of this process may be oligarchic growth in which a giant-planet core grows by sweeping up smaller, asteroid-size planetesimals. Here, we describe new numerical simulations of oligarchic growth using a particle-in-a-box model. The simulations include several processes that can effect oligarchic growth: (i) planetesimal fragmentation due to mutual collisions, (ii) the modified capture rate of planetesimals due to a core's atmosphere, (iii) drag with the disk gas during encounters with the core (so-called "pebble accretion"), (iv) modification of particle velocities by turbulence and drift caused by gas drag, (v) the presence of a population of mm-to-m size "pebbles" that represent the transition point between disruptive collisions between larger particles, and mergers between dust grains, and (vi) radial drift of small objects due to gas drag. Collisions between planetesimals rapidly generate a population of pebbles. The rate at which a core sweeps up pebbles is controlled by pebble accretion dynamics. Metre-size pebbles lose energy during an encounter with a core due to drag, and settle towards the core, greatly increasing the capture probability during a single encounter. Millimetre-size pebbles are tightly coupled to the gas and most are swept past the core during an encounter rather than being captured. Accretion efficiency per encounter increases with pebble size in this size range. However, radial drift rates also increase with size, so metre-size objects encounter a core on many fewer occasions than mm-size pebbles before they drift out of a region. The net result is that core growth rates vary weakly with pebble size, with the optimal diameter being about 10 cm. The main effect of planetesimal size is to determine the rate of mutual collisions, fragment production and the formation of pebbles. 1-km-diameter planetesimals collide frequently and have low impact strengths, leading to a large surface density of pebbles and rapid core growth via pebble accretion. 100-km-diameter planetesimals produce fewer pebbles, and pebble accretion plays a minor role in this case. The strength of turbulence in the gas determines the scale height of pebbles in the disk, which affects the rate at which they are accreted. For an initial solid surface density of 12 g/cm^2 at 5 AU, with 10-cm diameter pebbles and a disk viscosity parameter $\alpha = 10^{-4}$, a 10-Earth mass core can form in 3 My for 1–10 km diameter planetesimals. The growth of such a core requires longer than 3 My if planetesimals are 100 km in diameter.

1. Introduction

The formation of gas giant planets such as Jupiter is a long-standing problem in planetary science. Giant planets contain large amounts of hydrogen and helium, which were almost certainly captured as gasses from the planets' protoplanetary disks. Giant planets are observed to orbit a sizeable fraction of stars (Cumming et al., 2008), yet a typical protoplanetary disk has a lifetime of only a few million years (Haisch et al., 2001; Williams, 2012). A successful model for giant planet formation needs to explain both why they form around so many stars, and how they form in such a short time.

In the popular core-accretion model (Pollack et al., 1996), giant planets form in a two-step process. In the first step, dust grains in a protoplanetary disk coalesce due to electrostatic forces and gravity to form a large solid body that will become the core of a giant planet. As it grows larger, a core acquires an atmosphere captured from the disk that grows more massive as the core mass increases. For low-mass cores, hydrostatic pressure in the atmosphere balances gravity and the atmosphere is stable. When the core mass exceeds a critical value of order 1–10 Earth masses (Ikoma et al., 2000), this equilibrium breaks down (Mizuno, 1980; Stevenson,

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1982). Gas then flows onto the core at an increasing rate, forming a massive gaseous envelope around a solid core.

The time required for a critical mass core to accrete a massive envelope depends on the opacity, which is set mainly by the size of dust grains embedded in the gas (Ikoma et al., 2000). Recent studies suggest dust grains in an envelope are likely to coagulate into aggregates on a short timescale, substantially reducing the opacity (Movshovitz and Podolak, 2008) and allowing rapid gas accretion. As a result, a critical mass core can grow to Jupiter's mass on a timescale of order 1 myr (Movshovitz et al., 2010), comfortably within the lifetime of a typical disk.

It is less clear how the critical-mass cores themselves form, and how they do so rapidly enough to accrete gas before a disk disperses. Laboratory experiments show that μm-sized dust grains readily coagulate into mm-to-cm-sized particles due to electrostatic forces (Blum and Wurm, 2008). As particles grow larger their relative velocities increase due to interactions with the gas. Gas pressure in a disk generally decreases with distance from the star, so that gas orbits more slowly than solid objects. As a result, small particles experience a strong headwind that causes them to drift radially and tangentially with respect to larger objects (Weidenschilling, 1977). The relative velocities of small particles are also increased by turbulent eddies within the gas (Ormel and Cuzzi, 2007). Both processes peak at particle sizes of order 1 m, with relative velocities measured in tens of m/s (Weidenschilling, 1977; Ormel and Cuzzi, 2007). At these speeds, most collisions are likely to result in bouncing or erosion rather than growth (Ueda et al., 2001; Zsom et al., 2010). Simulations suggest that growth stalls at sizes somewhere between 1 mm and 1 m as a result (Brauer et al., 2008; Zsom et al., 2010) (but see Windmark et al., 2012).

Recently, two models have been developed that overcome this 'metre size barrier' to growth, each of which leads to the formation of asteroid-sized planetesimals directly from small particles without passing through intermediate sizes. In one model, dust coagulation initially forms a large population of cm-to-m-diameter particles. These objects respond to turbulent fluctuations in the gas, moving rapidly towards the nearest local maximum in the gas pressure (Johansen et al., 2006). When enough particles accumulate in one region, they begin to drag along the gas, reducing their own drift motion as a result. Other particles drifting from further out in the disk pile up in over-dense regions, a feedback referred to as the 'streaming instability' (Youdin and Goodman, 2005; Johansen et al., 2009; Bai and Stone, 2010). The resulting particle concentrations can potentially form gravitationally bound clumps that shrink to form solid planetesimals (Johansen et al., 2011, 2012). In the 'turbulent concentration' model, particle coagulation stalls at mm sizes. These particles are strongly affected by small turbulent eddies, becoming concentrated in stagnant regions between the eddies (Cuzzi et al., 2008). Calculations suggest these concentrations can occasionally become dense enough to form gravitationally bound clumps and ultimately planetesimals (Cuzzi et al., 2010; Chambers, 2010) (but see (Pan et al., 2011).

Both the turbulent concentration and streaming instability models predict the formation of planetesimals of order 100–1000 km in size (Cuzzi et al., 2010; Chambers, 2010; Johansen et al., 2011). These predictions are in good agreement with the results of simulations that attempt to explain the modern size distribution of the main asteroid belt (Morbidelli et al., 2009) (but see Weidenschilling, 2011). This size distribution shows a change of slope at a diameter ~100 km, and it has been argued that most objects larger than this size are primordial while most smaller bodies are fragments generated in catastrophic collisions (Bottke et al., 2005). If so, it is plausible that most planetesimals were also ~100 km in size.

It remains unclear how efficient planetesimal formation was in the solar nebula. Meteorite parent bodies exhibit a range of ages spanning several million years (Scott, 2007), which suggests that planetesimal formation was sporadic and protracted. As a result, it is possible that much of the solid material in a protoplanetary disk remains in the form of small particles long after the first planetesimals appear.

Planetesimals are massive enough that their gravity helps them to hold onto material during collisions, aiding growth. The rate at which planetesimals collide and grow is controlled by their relative velocities—a low encounter speed allows gravity to focus the trajectories of two planetesimals towards each other, increasing the chance of a collision. Over the course of many encounters, the largest planetesimals tend to acquire nearly circular, coplanar orbits, increasing their mutual collision probability (Kokubo and Ida, 1996). Smaller planetesimals have more inclined, elliptical orbits, and less chance of colliding. This leads to runaway growth in which the largest planetesimals grow at the fastest rate, eventually detaching themselves from the continuous planetesimal size distribution (Wetherill and Stewart, 1993).

Runaway growth ceases when gravitational perturbations from the largest planetesimals become more important than perturbations from the general population for determining the velocity distribution (Ida and Makino, 1993). At this point, growth slows down and becomes self regulated. Each region of a protoplanetary disk comes to be dominated by a single large planetesimal, commonly called a planetary embryo, that grows mainly by sweeping up planetesimals in the surrounding region called its feeding zone (Kokubo and Ida, 1998).

Oligarchic growth is likely to happen more slowly than runaway growth because an embryo's ability to stir up the relative velocities of nearby planetesimals increases as the embryo grows more massive (Ida and Makino, 1993). The short timescale required for gas accretion found in recent simulations (Movshovitz et al., 2010) suggests that the length of the oligarchic growth stage, and planetesimal formation itself, are the main factors that determine whether gas giant planets can form within the lifetime of a protoplanetary disk.

The timescale associated with oligarchic growth is likely to depend on the typical size of planetesimals for several reasons (Levison et al., 2010). Small planetesimals have lower relative velocities than large ones (for sizes much larger than 1 m) due to the effects of gas drag. This means small planetesimals will be swept up more rapidly than larger objects, and embryos will grow more rapidly in this case (Rafikov, 2004; Chambers, 2006b). During oligarchic growth, planetesimals are likely to collide at high speeds leading to collisional disruption in many cases and the formation of a cascade of collision fragments (Wetherill and Stewart, 1993). In principle, fragmentation can speed up oligarchic growth substantially since much of the solid mass is transferred to lower mass objects, effectively reducing the mass of a typical planetesimal (Inaba et al., 2003; Chambers, 2008; Kenyon and Bromley, 2009). However, excessive fragmentation may also cause oligarchic growth to stall as fragments drift inwards by gas drag and are lost (Kobayashi et al., 2010). It has also been suggested that small fragments never form in large numbers because the collisional cascade ceases due to the low relative velocities of the smallest particles (Kobayashi et al., 2011).

Embryos larger than the Moon capture substantial atmospheres from the surrounding gas disk. A planetesimal or collision fragment passing through an atmosphere experiences drag, and this is likely to increase the probability of capture, especially for small particles (Inaba and Ikoma, 2003). The presence of embryo atmospheres can substantially reduce oligarchic growth times as a result (Chambers, 2006a; Thommes et al., 2007).

The importance of drag with the disk gas during encounters between small particles and embryos has only been appreciated relatively recently. Calculations show that the combined effect of gas