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The great dichotomy of the Solar System: Small terrestrial embryos and massive giant planet cores

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ABSTRACT

The basic structure of the Solar System is set by the presence of low-mass terrestrial planets in its inner part and giant planets in its outer part. This is the result of the formation of a system of multiple embryos with approximately the mass of Mars in the inner disk and of a few multi-Earth-mass cores in the outer disk, within the lifetime of the gaseous component of the protoplanetary disk. What was the origin of this dichotomy in the mass distribution of embryos/cores? We show in this paper that the classic processes of runaway and oligarchic growth from a disk of planetesimals cannot explain this dichotomy, even if the original surface density of solids increased at the snowline. Instead, the accretion of drifting pebbles by embryos and cores can explain the dichotomy, provided that some assumptions hold true. We propose that the mass-flow of pebbles is two-times lower and the characteristic size of the pebbles is approximately ten times smaller within the snowline than beyond the snowline (respectively at heliocentric distance $r < r_{ice}$ and $r > r_{ice}$, where r_{ice} is the snowline heliocentric distance), due to ice sublimation and the splitting of icy pebbles into a collection of chondrule-size silicate grains. In this case, objects of original sub-lunar mass would grow at drastically different rates in the two regions of the disk. Within the snowline these bodies would reach approximately the mass of Mars while beyond the snowline they would grow to ~ 20 Earth masses. The results may change quantitatively with changes to the assumed parameters, but the establishment of a clear dichotomy in the mass distribution of protoplanets appears robust provided that there is enough turbulence in the disk to prevent the sedimentation of the silicate grains into a very thin layer.

1. Introduction

The Solar System has a characteristic structure, with low-mass rocky planets in its inner part, often called terrestrial planets, and giant planets (gas-dominated or ice-dominated) in the outer part.

A census of protoplanetary disks in clusters with known ages shows that the dust emission (usually assumed to trace the abundance of gas) disappears in a few My (Haisch et al., 2001); this is also the timescale on which the emission lines diagnostic of gas accretion onto the central star fade away (Hartmann et al., 1998). The fact that no primitive chondrite parent bodies seem to have accreted beyond 3–4 My (Kleine et al., 2005) suggests that the proto-Solar-System disk was not of exceptional longevity.

Clearly, the giant planets had to form within the lifetime of the gas-disk because they accreted substantial amounts of hydrogen and helium (this is true also for Uranus and Neptune). Thus giant planets should have formed within a few My only. The commonly accepted scenario for giant-planet formation is the core-accretion model (Pollack et al., 1996). In short, a massive solid core accretes first and then it captures a massive atmosphere of H and He from the protoplanetary disk. The mass of all giant planet cores but Jupiter is around 10 Earth masses ($M_\oplus$) (Guillot, 2005). Jupiter might have no core today (Nettelmann et al., 2008). However, there are several tens of Earth masses of "metals" (molecules heavier than H and He) in Jupiter (Guillot, 2005) and it is possible that part or even most of its primordial core has been eroded and dissolved into the atmosphere (Guillot et al., 2004; Wilson and Militzer, 2012).

An estimate of the mass of the core needed for the accretion of a massive atmosphere is also provided by models. It is generally considered, since the work of Pollack et al., that the core needs to exceed $\sim 10\,M_\oplus$. More precisely, the critical mass for the runaway accretion of the atmosphere depends on the rate at which the core

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accretes solids, on the molecular weight of the atmosphere (Ikoma et al., 2000; Hori and Ikoma, 2011) and the dust opacity in the envelope (Mizuno, 1980; Stevenson, 1982), which remains poorly known despite modern attempts to estimate the dust opacity self-consistently by modeling the aggregation of infalling grains (Movshovitz and Podolak, 2008; Ormel, 2014). The solid accretion rate could not be arbitrarily small, otherwise the core would not have formed in first place within the lifetime of the disk. This gives a constraint on the minimal mass of the core. Lambrechts et al. (2014, see their Fig. 7) showed that the core should have had a mass of at least 10 $M_\oplus$, if the ratio H_2O/H_2 in the atmosphere was less than 0.6. Uranus and Neptune provide an indirect confirmation of this estimate as a lower-bound for the core mass. In fact, they have a core of about 10–15 $M_\oplus$ (Guillot, 2005) and only a few Earth masses of H and He, which means that they either did not start runaway accretion of gas, or did so only at the very end of the lifetime of the disk.

The situation for the terrestrial planets is completely different. There is a general consensus that the terrestrial planets formed from a system of planetary embryos and planetesimals (see Morbidelli et al., 2012, for a review), although the details of how this happened can differ from one model to the other (Chambers and Wetherill, 1998; Chambers, 2001; Agnor et al., 1999; Raymond et al., 2004, 2006a,b; O'Brien et al., 2006; Hansen, 2009; Walsh et al., 2011; Jacobson and Morbidelli, 2014). According to these models and to the interpretation of isotopic chronometers for terrestrial and lunar samples (Yin et al., 2002; Jacobsen, 2005; Touboul et al., 2007; Allegre et al., 2008; Halliday, 2008; Taylor et al., 2009) the Earth took several tens of My to complete its formation, with a preferred timing for the Moon forming event around 100 My (Jacobson et al., 2014). The minimum time in which the Earth acquired 63% of its mass is 11 My (Yin et al., 2002; Jacobsen, 2005). Thus, most of the assemblage of the Earth clearly took place after the removal of the gas from the protoplanetary disk.

Mars, instead, formed very quickly, i.e. in a few My (Halliday and Kleine, 2006; Dauphas and Pourmand, 2011), basically on the same timescale of chondritic parent bodies. This suggests that Mars is a stranded embryo (Jacobson and Morbidelli, 2014). The fact that the Moon-forming projectile also had a mass of the order of a Mars-mass (Canup and Asphaug, 2001; Cuk and Stewart, 2012) and that Mercury, if it had originally the same iron content as the other terrestrial planets, was also approximately Mars-mass (Benz et al., 1988) suggests that the mass of Mars was the typical mass of planetary embryos in the inner Solar System at the time the gas was removed from the protoplanetary disk.

In summary, it appears compelling that, by the time gas was removed from the system, the process of formation of the solid component of planets had produced a great dichotomy in the mass distribution of protoplanets: in the inner system, the largest objects were approximately Mars-mass; in the outer Solar System they were $\sim 10\,M_\oplus$. Thus, there was a contrast of two orders of magnitude between the masses of the solid planets formed in the inner and outer systems respectively. This happened despite the accretion timescale, which can be reasonably approximated by the orbital timescale, is 10 times faster at 1 AU than 5 AU!

How could this be possible? The generic (and hand-waving) explanation is that the cores of the giant planets formed beyond the ice line, so that the density of solids was comparatively larger than in the inner Solar System, where only refractory material could be in solid form. However, this cannot be the explanation. According to Lodders (2003), for the solar abundance the H_2O-ice/rock ratio is approximately one-to-one. That means that the amount of solid mass available for planet formation beyond the snowline increases by just a factor of 2. This is confirmed by the ice/rock ratio inferred for comets, trans-Neptunian objects, and irregular satellites of giant planets (McDonnell et al., 1987; Stern et al., 1997; Johnson and Lunine, 2005). An enhancement of the solid mass by more than a factor of 2 might have been produced by the so-called "cold-finger effect" (Morfill and Voelk, 1984; Ros and Johansen, 2013), but this would have happened only locally at the snowline and therefore could explain at most the formation of one giant-planet core, not several.

The purpose of this paper is to investigate which process of planet formation is more likely to have led to the dichotomy discussed above. In Section 2 we consider the classical process of formation of embryos/cores by runaway/oligarchic accretion of planetesimals (Greenberg et al., 1978; Kokubo and Ida, 1998; Wetherill and Stewart, 1993; Weidenschilling et al., 1997). We show that this process clearly cannot explain the dichotomy. Next, in Section 3, we consider the process of pebble accretion. This is a new process for planet growth, introduced in Lambrechts and Johansen (2012; see also the precursor work by Ormel and Klahr (2010), Johansen and Lacerda (2010), Murray-Clay et al. (2011), and Bromley and Kenyon (2011)), which is rapidly gaining attention (Morbidelli and Nesvorny, 2012; Chambers, 2014; Lambrechts and Johansen, 2014; Lambrechts et al., 2014; Guillot et al., 2014; Kretke and Levison, 2014a,b). We will show that, provided some assumptions hold true, the pebble accretion process can explain the two orders of magnitude mass-contrast between inner Solar System objects and outer Solar System objects. The conclusions and perspectives are discussed in Section 4.

2. Growth of embryos and cores by planetesimal accretion

The growth of embryos and cores from a disk of planetesimals proceeds in two phases.

The first phase is that of runaway growth (Greenberg et al., 1978). Here most of the mass of the disk is in "small" planetesimals. The velocity dispersion of the planetesimals is set by the equilibrium between the self-excitation of their orbits, also called self-stirring, and gas drag. We neglect here collisional damping because it is important only for very small objects, which we will call pebbles in the next section, and in the absence of gas drag (Goldreich et al., 2004; Levison and Morbidelli, 2007). The velocity dispersion of the planetesimals is therefore comparable or smaller (because of the drag) to the escape velocity from the surface of the planetesimals carrying the bulk of the population mass (Greenberg et al., 1978). In this situation, the accretion cross section σ of an individual planetesimal is:

$$\sigma = \pi R^2 \left(1 + \frac{V_{esc}^2}{V_{rel}^2}\right), \tag{1}$$

where R is the planetesimal radius, V_{esc} is the escape velocity from the planetesimal surface, V_{rel} is the dispersion velocity in the planetesimal disk and the term in parenthesis is called the "gravitational focusing factor" (Greenberg et al., 1978; Greenzweig and Lissauer, 1990, 1992). Thus, the most massive planetesimals have a comparative advantage. If their V_{esc} is significantly larger than V_{rel}, their gravitational focusing factor can be approximated by $V_{esc}^2/V_{rel}^2 \propto M^{2/3}/V_{rel}^2$, where M is their mass. Because the accretion rate is proportional to σ and $R \propto M^{1/3}$, from (1) the relative mass accretion rate of the massive bodies is:

$$\frac{1}{M}\frac{dM}{dt} \propto M^{1/3}. \tag{2}$$

Eq. (2) means that the most massive bodies grow the fastest and their mass ratio with the rest of the planetesimal population increases exponentially with time. Hence the name "runaway growth".