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Rapid planetesimal formation in the inner protoplanetary disk

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Abstract. Growth barriers, including the bouncing, fragmentation and radial drift problems, are still a big issue in planetesimal and thus planet formation theory. We present a new mechanism for very rapid planetesimal formation by sweep-up growth. Planetesimal formation is extremely fast in the inner protoplanetary disk where the growth rate exceeds the radial drift rate, leading to local planetesimal formation and pile-up inside of 1 AU. This scenario is very appealing particularly in the context of explaining the low mass of Mars, as well as the formation of recently discovered multi-transiting systems with tightly-packed inner planets.

Keywords. accretion, accretion disks, stars: circumstellar matter, planetary systems: protoplanetary disks, planetary systems: formation, solar system: formation, methods: numerical

1. Introduction

Planet formation takes place in disks surrounding young stars. It starts with μm-sized grains, which are already present in the interstellar medium. The journey from a μm-sized monomer to a 1000 km-sized planet covers 40 orders of magnitude in mass and comprises many intermediate steps. Tiny monomers are known to easily coagulate to mm-sized aggregates that are held together solely by material strength. On the other side of the mass range, km-sized planetesimals are held together by self-gravity. The particles between the dust aggregates and planetesimals are often called pebbles. However, a number of growth barriers have been identified that aggravates the pebble formation.

Evolution of the solid material in a protoplanetary disk is driven by its interaction with gas. Due to pressure support, the gas disk is rotating with a slightly sub-Keplerian velocity and thus the dust particles feel a constant headwind. The grains lose their angular momentum due to aerodynamic drag and drift towards the star. The velocity of the inward drift is determined by the radial pressure gradient and particle size. Particles of different sizes acquire different systematic drift speeds and thus relative velocities that drive their collisions. As the radial drift velocity in a standard disk model is as high as 30 m s^{-1}, the loss of solids and the high impact speed collisions pose major problems in growing large bodies. Panel a) of Fig. 1 shows a map of the growth barriers in a Minimum-Mass Extrasolar Nebula disk (Chiang & Laughlin 2013) in terms of the distance from the star and dust grain size. The gray region corresponds to the radial drift barrier, where the timescale of inward drift is shorter than the growth timescale. It is located in the outer part of the disk, meaning that all larger grains in this region are efficiently removed by the drift. The large grains drift until they reach inner regions (< 10 AU in this example) where the Stokes drag triggers rapid grain growth (Birnstiel *et al.* 2010, Okuzumi *et al.* 2012). However, the high velocity collisions leading to bouncing, erosion

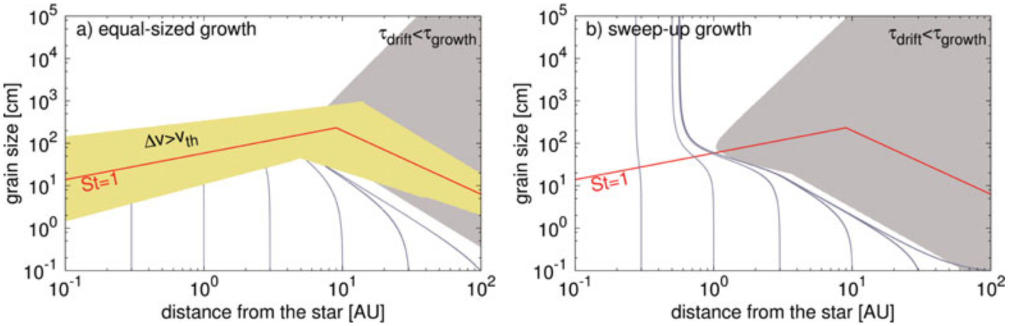

Figure 1. Maps of the growth barriers: the radial drift barrier (gray region) and the fragmentation barrier (yellow region), and evolution of test particles (gray lines): a) for the usual, equal–sized growth mode, b) for the sweep-up growth. The red line corresponds to aggregates with Stokes number of unity, which have the highest radial drift and impact velocities. The change of slope comes from the change of the drift regime form Epstein (outer disk) to Stokes (inner disk). The fragmentation barrier corresponds to impact velocities higher than $v_{\rm th} = 10$ m s^{-1}.

and fragmentation of dust aggregates do not allow formation of pebbles in the inner part of the disk. The interplay between drift and growth timescales leads to redistribution of initially homogeneous material and a solid-depleted outer disk (Birnstiel *et al.* 2012).

A number of possible solutions to the growth barriers problem have been suggested over the years. Whipple (1972) proposed that local inhomogeneities in the protoplanetary disk structure can reduce or reverse the pressure gradient (*pressure bumps*). This leads to a reduction of the inward drift and local enhancement of dust abundance as well as limiting the impact speeds, and therefore facilitates planetesimal formation (Brauer *et al.* 2008, Drążkowska *et al.* 2013). Specific kinds of pressure bumps are also required by the streaming instability scenario, where pebbles form clumps that are dense enough to gravitationally collapse to 100 km-sized planetesimals (Johansen *et al.* 2007). However, the formation mechanism and lifetimes of such pressure bumps are not yet well understood and the grain sizes required for streaming instability to trigger are hard to obtain due to bouncing and fragmentation. In this work, we focus on the idea of sweep-up growth and show that planetesimals can form in the inner disk, even without pressure bumps.

2. Sweep-up and pile-up scenario

Sweep-up growth Laboratory experiments show that even very high impact speed collisions may lead to a net growth of a target particle if the mass ratio of the colliding aggregates is high (Wurm *et al.* 2005, Teiser & Wurm 2009, Meisner *et al.* 2013). These are fragmentation with mass transfer collisions and the corresponding growth mode is called sweep-up growth (Windmark *et al.* 2012a). The growth barriers, however, hinder the formation of any larger aggregates that could benefit from this process. A solution for this problem may be the impact velocities distribution produced by turbulence present in the disk. Around 1 in 10^{30} aggregates may be "lucky" and participate only in low-velocity collisions until they grow to a size from which they can grow by the sweep-up process (Windmark *et al.* 2012b, Garaud *et al.* 2013, Drążkowska *et al.* 2014).

Pile-up While it has been previously postulated that the radial drift may lead to a pile-up of the solid material in the inner disk (Youdin & Shu 2002, Laibe *et al.* 2012), the interplay between dust drift and growth was investigated only briefly. We show that including both growth and drift leads to the conclusion that planetesimals can only form and survive in the inner part of the disk, where the growth rate exceeds the drift rate.

Panel b) of Fig. 1 shows the evolution of test particles undergoing the radial drift and

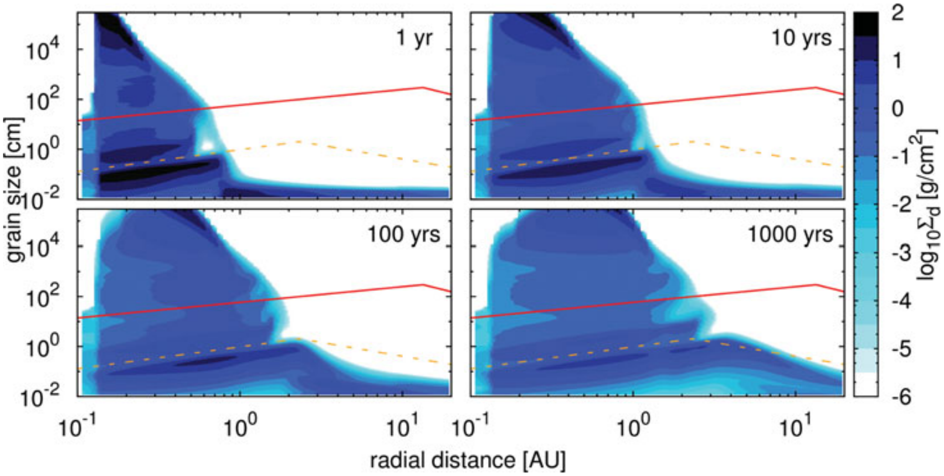

Figure 2. Results of the dust coagulation simulation with the sweep-up growth and impact velocity distribution enabled. The panels show color-coded surface density of dust aggregates. Planetesimals are formed very efficiently inside of 1 AU. The original fragmentation barrier, marked with the orange dashed line, is still impacting the outcome: only some fraction of dust aggregates is able to overcome it. The solid red line corresponds to the Stokes number of unity.

growing via the sweep-up of μm-sized monomers. The drift barrier is more pronounced than in the equal-sized growth case (panel a) because the sweep-up growth rate is lower. However, the region that is free of the drift barrier still exists inside 1 AU and this is where our growing test particles pile-up, indicating that planetesimals should be able to both form and remain there.

We check the predictions of the toy model, which comprises only a simplified prescription for drift and growth of test particles, by direct numerical simulations using a dust coagulation code based on the code presented by Birnstiel *et al.* (2010). We implement a Maxwellian impact velocity distribution that allows us to overcome the growth barriers (Windmark *et al.* 2012b). Results obtained with this model are presented in Fig. 2. A population of km-sized planetesimals is formed very quickly inside of 1 AU, but a large population of small aggregates is also present due to the original fragmentation barrier. Redistribution of the solid material by the radial drift leads simultaneously to significant pile-up in the inner disk, reaching a few times the initial dust-to-gas ratio, and to depletion of solids beyond 1 AU. The results presented in this contribution will be described in more detail in Windmark *et al.* (2014).

3. Summary and possible applications

We present a new scenario of rapid planetesimal formation in the inner part of the protoplanetary disk. We explain this scenario using a simple toy model and confirm it with direct numerical simulations. Including both the radial drift and dust growth is crucial for this scenario, as it emerges from the interplay between the two processes. This interplay leads to redistribution of solids, causing a significant pile-up in the inner disk. At the same time, larger bodies are growing very efficiently inside of 1 AU and a relatively narrow planetesimal rim is formed. Comparing to other planetesimal formation scenarios, the scenario we suggest is particularly appealing because it does not require any additional conditions beyond a standard disk model. It is particularly interesting in the context of the following issues:

Low mass of Mars Raymond *et al.* (2009) showed that attempting to reproduce the final assembly of the inner Solar System starting from an initially uniform distribution of planetesimals leads to mass for Mars significantly higher than observed. Hansen (2009) found that the mass of Mars can be reproduced if all the planetesimals are initially packed in a narrow annulus between 0.7 AU and 1 AU. Standard explanation of this setup involves the Grand Tack scenario, where Jupiter migrates inwards and the gravitational interactions truncate the planetesimal disk at roughly 1 AU. Subsequent planetesimal accretion gives a mass for Mars consistent with observations (Walsh *et al.* 2011). Most recently, Izidoro *et al.* (2014) showed that the low mass of Mars can be reproduced using a disk with an initial ad-hoc depletion of solids between 1 AU and 2 AU. Our scenario may naturally produce planetesimal distribution required to reproduce the masses of inner Solar System planets and we are going to investigate this in our future work.

Systems with tightly-packed inner planets The *Kepler* mission has found hundreds of new exoplanets. Many of them are in multiple systems, with 3 to 5 planets with orbital periods of less than 100 days and very low inclinations (Fang & Margot 2012). These multi-transiting systems with tightly-packed inner planets could form by migration of planets from the outer disk (Raymond & Cossou 2014), but this would lead to mean-motion resonances, which are only observed in some of the systems. The planetesimal formation scenario we present suggests that in-situ formation of these systems is a natural outcome of solid material evolution in a gas-rich protoplanetary disks.

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