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"PARTICLE TRAPS" AT PLANET GAP EDGES IN DISKS: EFFECTS OF GRAIN GROWTH AND FRAGMENTATION

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Abstract. We model the dust evolution in protoplanetary disks (PPD) with 3D, Smoothed Particle Hydrodynamics (SPH), two-phase (gas+dust) hydrodynamical simulations. The gas+dust dynamics, where aerodynamic drag leads to the vertical settling and radial migration of grains, is consistently treated. In a previous work, we characterized the spatial distribution of non-growing dust grains of different sizes in a disk containing a gap-opening planet and investigated the gap's detectability with ALMA. Here we take into account the effects of grain growth and fragmentation and study their impact on the distribution of solids in the disk. We show that rapid grain growth in the "particle traps" at the edges of planet gaps are strongly affected by fragmentation. We discuss the consequences for ALMA and NOEMA observations.

Keywords: protoplanetary disks, planet-disk interactions, hydrodynamics, methods: numerical, submillimeter: planetary systems

1 Introduction

Planets are thought to form from the aggregation of sub-μm dust grains in PPD around young stars. While small dust grains easily stick during collisions to form aggregates up to cm or dm sizes, the subsequent growth to planetesimal size is probably the biggest problem in the theory of planet formation. Three "barriers" to planet formation, preventing this step, have been identified. The radial-drift barrier (Weidenschilling 1977; Laibe et al. 2012; Laibe 2014) occurs when grains are migrating inwards due to gas drag so rapidly that they fall onto the star in a fraction of both the disk lifetime and the planet formation timescale. This is the case for cm- to m-sized grains, whereas small grains are strongly coupled to the gas and follow its motion, and large grains are largely insensitive to gas drag and stay on their Keplerian orbits. However, Laibe et al. (2008) showed that growing grains can overcome the fast-migration regime and decouple from the gas before being lost from the disk. The fragmentation barrier (Dullemond & Dominik 2005; Blum & Wurm 2008) happens when dust grains collide at relative velocities too high for them to stick, they instead shatter upon impact. Finally, the bouncing barrier (Zsom et al. 2010; Windmark et al. 2012) occurs at velocities lower than the fragmentation threshold, when grains bounce off each other. Accounting for stochastic motion, Garaud et al. (2013) showed that the low-velocity tail of the distribution allowed collisional growth to larger sizes, thus overcoming both the bouncing and fragmentation barriers.

"Particle traps" are other solutions to the barriers of planet formation, they are locations of pressure maximum, towards which gas drags the dust grains. The concentration of grains lowers their relative velocities and eases their growth. Several types of particle traps have been proposed: anticyclonic vortices (Barge & Sommeria 1995; Méheut et al. 2012), the snow line or the dead zone (Kretke & Lin 2007; Dzyurkevich et al. 2010), planet gap edges (Fouchet et al. 2007, 2010; Gonzalez et al. 2012), or any kind of "pressure bump" in the gas surface density (Pinilla et al. 2012). In this study, we focus on particle traps at planet gap edges.

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2 Hydrodynamical simulations

In a previous work (Fouchet et al. 2010), we ran simulations of the dynamics of grains of constant size in a PPD containing a planet using our 3D, two-fluid (gas+dust), SPH code (Barrière-Fouchet et al. 2005). We modeled a disk of mass $M_{\rm disk} = 0.02\ M_\odot$ orbiting a 1 $M_\odot$ star and containing 1 % of dust by mass. We studied the evolution of the dust phase for grains of 100 μm, 1 mm and 1 cm and for planets of 0.1, 0.5, 1 and 5 $M_{\rm J}$, on a circular orbit of radius 40 AU. We found that in all cases, the gap created in the dust phase was deeper and wider than in the gas, as a result of the dust motion towards the gas pressure maxima at the gap edges. We computed synthetic ALMA images of our simulated disks with a 1 and a 5 $M_{\rm J}$ planet (Gonzalez et al. 2012). We found that gap detection is robust and that ALMA should discover a large number of them.

We now study the effect of grain growth and fragmentation on the dust dynamics in the same disk containing a 5 $M_{\rm J}$ planet on the same orbit. Grain growth is implemented in our code as detailed in Laibe et al. (2008). We introduce fragmentation by defining a velocity threshold $V_{\rm frag}$, to which we compare the relative velocity $V_{\rm rel}$ of dust grains. When $V_{\rm rel} < V_{\rm frag}$, grains grow and when $V_{\rm rel} > V_{\rm frag}$, they shatter, leading to a decrease of the size of the representative SPH particles. $V_{\rm frag}$ is a free parameter of our simulations and we assume it to be constant. We ran simulations for pure growth (equivalent to $V_{\rm frag} = +\infty$) and with fragmentation for $V_{\rm frag} = 10$, 15, 20 and 25 m s^{-1}. We start from an initially uniform grain size $s_0 = 10\ \mu$m. Both gas and dust phases contain 200,000 SPH particles and all simulations were evolved for 100 000 yr.

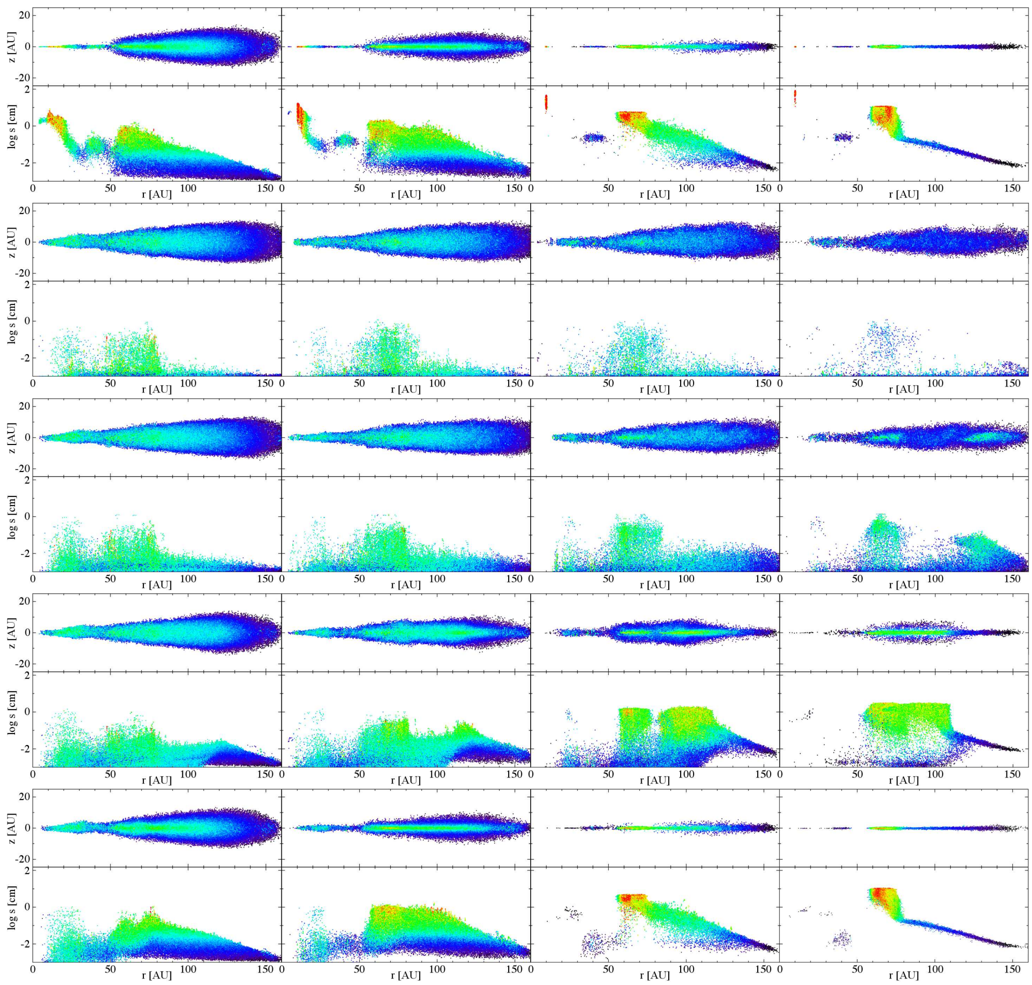

Fig. 1. Time evolution of the dust phase in the simulation with pure growth and with fragmentation for $V_{\rm frag} = 10$, 15, 20 and 25 m s^{-1}, from top to bottom. For each simulation, the top panel show a meridian plane cut of the dust distribution and the bottom panel shows the radial grain size distribution. *From left to right:* Snapshots at $t = 6\,000$, 12 000, 25 000 and 50 000 yr. The color represents the volume density, from 10^{-15} (black) to 5×10^{-11} kg m^{-3} (red).

Figure 1 shows the dust distribution in the meridian plane together with the radial distribution of grain sizes at $t = 6\,000$, $12\,000$, $25\,000$ and $50\,000$ yr for the five simulations. In the pure growth case, as was found by Laibe et al. (2008) in a disk without planets, particles typically grow as they settle to the midplane, then enter the fast migration regime while experiencing little growth. Grains initially close to the disk inner edge are thus lost to the star, as is the case for the moderately dense clump of centimetric particles seen interior to 10 AU in the 6 000 yr snapshot. Further out, grains migrate towards and accumulate at both gap edges, where their density is higher and their growth more efficient. At 12 000 yr, the detached group of particles at the disk inner edge contains the last grains to be lost to the star. Just outside of 10 AU, particles have outgrown the fast migration regime (for ~ 1 cm here), are now decoupled from the gas and grow without migrating. At 25 000 yr, all grains in the inner disk are concentrated in a narrow, dense ring where they grow further. The outer gap edge has also become very dense. Finally, at 50 000 yr, the gap only contains particles that are trapped in corotation with the planet. Large grains are present at both gap edges, showing the efficiency of these particle traps in helping to form solids larger than the cm sizes. Gap edges therefore appear as potential sites for the formation of additional planets.

When fragmentation is included, for $V_{\rm frag} = 10$ and 15 $\rm m\,s^{-1}$ grains are not able to grow large enough in the inner disk to overcome the radial-drift barrier. The inner disk is progressively lost to the star. For $V_{\rm frag} = 10$ $\rm m\,s^{-1}$, fragmentation even prevents the majority of the grains from decoupling from the gas, they therefore follow the gas through the gap and migrate into the inner disk where their inward drift continues. The dust disk slowly drains and its density after 50 000 yr is very low. For $V_{\rm frag} = 15$ $\rm m\,s^{-1}$, the planet gap is shallow, but the density difference is large enough to trap grains at the outer gap edge, where they start to overcome the fast migrating regime after 25 000 yr and grow slowly to reach cm sizes at 50 000 yr. In the very outer disk regions, the relative velocities between grains are low enough to remain below the fragmentation threshold and allow them to grow very slowly. Higher threshold values of $V_{\rm frag} = 20$ and 25 $\rm m\,s^{-1}$ help to retain more grains in the inner disk and a fraction of them overcomes the radial-drift barrier. A small population of grains survive in the inner disk after 25 000 yr, but do not grow much larger than cm sizes due to a limited reservoir. For $V_{\rm frag} = 20$ $\rm m\,s^{-1}$, growth is more efficient at the outer gap edge as well as in the disk outer regions, so that an extended ring of cm grains forms at 50 000 yr. For $V_{\rm frag} = 25$ $\rm m\,s^{-1}$, the outer disk is almost unaffected by fragmentation: it is very similar to the case with pure growth, with very efficient growth past cm sizes in a dense ring at the outer gap edge.

The fragmentation barrier appears as a major problem here. Low values of $V_{\rm frag} \sim 1 - 10$ $\rm m\,s^{-1}$, are usually favored and are considered in most studies (e.g. Birnstiel et al. 2010; Pinilla et al. 2012)), they do not lead to any significant growth past the radial-drift barrier. Planets do exist however, and grains must be able to grow in PPD. Is this possible for $V_{\rm rel} \geq 20$ $\rm m\,s^{-1}$? The answer seems to be yes. When taking into account grain porosity, numerical simulations have obtained values of $V_{\rm frag}$ of several tens of $\rm m\,s^{-1}$ (Wada et al. 2009; Meru et al. 2013). Both laboratory experiments (Teiser & Wurm 2009) and N-body simulations (Wada et al. 2013) have shown that mass transfer in high mass ratio collisions can lead to even higher values. Even if such cases represent only a fraction of all grain collisions in PPD, they may be enough to allow part of the dust population to grow to eventually form planetesimals.

3 Synthetic images

In order to determine the impact of growth and fragmentation on the planet gap detectability with ALMA and to assess whether the fragmentation threshold can be constrained by observations, we computed synthetic images from the resulting disk structure of each of our simulations. We first used the 3D Monte Carlo continuum radiative transfer code MCFOST (Pinte et al. 2006, 2009) to produce raw intensity maps from the dust distributions. These maps were then passed to the CASA* simulator for ALMA, to obtain synthetic images for a given observing configuration (wavelength, angular resolution, integration time). The procedure is described in detail in Gonzalez et al. (2012). To better compare with the images produced in the case of non-growing grains, we chose the standard disk parameters of Gonzalez et al. (2012): nearly face-on orientation, a distance $d = 140$ pc, a declination $\delta = -23^\circ$ and their optimal observing parameters for gap detection: integration time $t = 1$ h and angular resolution $\theta = 0.1''$ for 4 different wavelengths: 350 μm, 850 μm, 1.3 mm and 2.7 mm. The resulting images can also be used to estimate NOEMA's ability to detect gaps since it will reach a similar angular resolution to a factor of 2 at most. The smaller number of antennas will be partly compensated by

*`http://casa.nrao.edu`

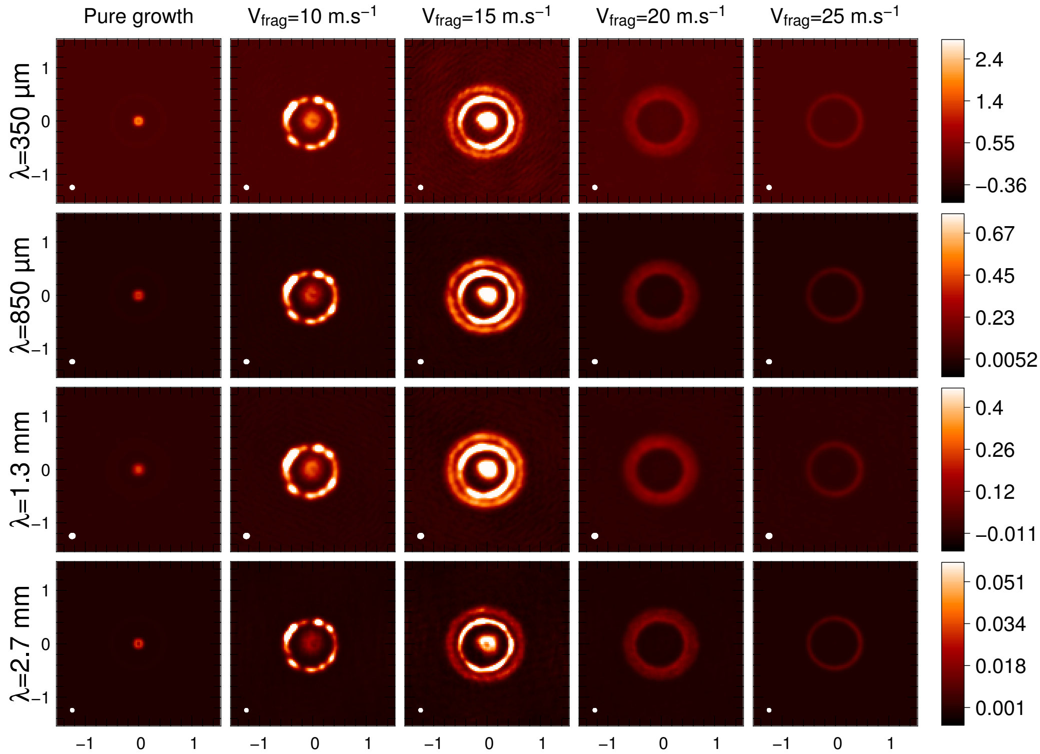

Fig. 2. Simulated ALMA observations of a disk viewed face-on at $d = 140$ pc and $\delta = -23^\circ$ for an integration time of 1 h and angular resolution of $0.1''$. *From left to right:* Simulations with pure growth and with fragmentation for $V_{\rm frag} = 10$, 15, 20 and 25 $\mathrm{m\,s^{-1}}$. *From top to bottom:* $\lambda = 350$ μm, 850 μm, 1.3 mm and 2.7 mm. The scale on each image is in arcseconds, with the beam size represented at its bottom left corner, and the colorbar gives the flux in mJy/beam. (Note that the flux scale changes in each row, due to the different beam size.)

better sensitivy and by the longer exposure times needed for *uv*-plane coverage, thus allowing to reach similar fluxes. The images for pure growth and the four different fragmentation thresholds are shown in Fig. 2.

The images do not show the gap for all simulations. Indeed, the disk appearance at a given wavelength results from a combination of the dust density and the grain size. For non-growing grains (Gonzalez et al. 2012), computations chose grain sizes that contribute the most to the ALMA wavelengths and the planet gap was prominent in all cases. For growing and fragmenting grains, their sizes evolve and may end up outside the optimal range ($s \sim 20$ μm $-$ 1 mm for $\lambda = 350$ μm to 2.7 mm) for most of the dust population. This is the case when grains can efficiently reach large sizes: in the pure growth case or when $V_{\rm frag} \geq 20$ $\mathrm{m\,s^{-1}}$. Only a small fraction of grains have the appropriate sizes in a thin annulus in the outer disk, producing a faint ring in the images. For the pure growth case, the high density at the inner gap edge makes it detectable, even though the grain sizes are outside the optimal range. A prominent gap is seen only for the lower values $V_{\rm frag} = 10$ and 15 $\mathrm{m\,s^{-1}}$, for which there is a large enough population of grains of the right size at both gap edges. Unfortunately, the differences between each case are not large enough to unambiguously discriminate one from the other: the problem is too degenerate to constrain the fragmentation threshold.

4 Conclusion

We have run 3D hydrodynamical simulations of the evolution of dust grains in a PPD containing a planet in order to study the effect of growth and fragmentation on the formation of large solids at "particle traps" located at planet gap edges. Such traps are a possible solution to the barriers of planet formation, allowing the formation of planetesimals. We found that fragmentation strongly limits the growth of dust grains even in the presence of dust traps and, in combination with radial drift, contributes to the loss of the inner disk. However, large values of the fragmentation threshold ($V_{\rm frag} \geq 20$ $\mathrm{m\,s^{-1}}$), recently found to be realistc under certain conditions, allow grains to grow above centimetric sizes, and possibly to planetesimal sizes.

We produced synthetic images from our simulated disks and found that gap detection by ALMA or NOEMA is made more difficult by large values of the fragmentation threshold. However, discriminating between different values of $V_{\rm frag}$ from submillimeter images seems impractical without additional constraints.

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