Gap Formation in the Dust Layer of 3D Protoplanetary Disks

S. T. Maddison • L. Fouchet¹ and J.-F. Gonzalez

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Abstract We numerically model the evolution of dust in a protoplanetary disk using a two-phase (gas + dust) Smoothed Particle Hydrodynamics (SPH) code, which is non-self-gravitating and locally isothermal. The code follows the three dimensional distribution of dust in a protoplanetary disk as it interacts with the gas via aerodynamic drag. In this work, we present the evolution of a disk comprising 1% dust by mass in the presence of an embedded planet for two different disk configurations: a small, minimum mass solar nebular (MMSN) disk and a larger, more massive Classical T Tauri star (CTTS) disk. We then vary the grain size and planetary mass to see how they effect the resulting disk structure.

We find that gap formation is much more rapid and striking in the dust layer than in the gas layer and that a system with a given stellar, disk and planetary mass will have a different appearance depending on the grain size and that such differences will be detectable in the millimetre domain with ALMA. For low mass planets in our MMSN models, a gap can open in the dust disk while not in the gas disk. We also note that dust accumulates at the external edge of the planetary gap and speculate that the presence of a planet in the disk may facilitate the growth of planetesimals in this high density region.

Keywords planetary systems: protoplanetary disks – hydrodynamics – methods: numerical

1 Introduction

The effect of a planet in a gaseous disk has been well studied both analytically and numerically (Papaloizou & Lin 1984 [Kley 1999] [Bryden et al. 1999] [de Val-Borro et al. 2006]). Tidal torques resulting from the gravitational perturbation of the planet lead to an exchange in angular momentum which creates a gap around the planet. To sustain the gap in viscous disks, there needs to be a balance between the tidal torques, which clear the gap, and viscous torques, which fills the gap (Lin & Papaloizou 1979). Thus the gap criterion is given by

$$\frac{M_p}{M_*} > 40\alpha_{\text{SS}} \left( \frac{H}{r_p} \right)^2,$$

where $M_p$ and $M_*$ are the mass of the planet and star, $\alpha_{\text{SS}}$ is the Shakura & Sunyaev (1973) viscosity parameter, $H$ is the disk scale height and $r_p$ is the semi-major axis of the planet. Our previous simulations (Barrière-Fouchet et al. 2005, hereafter BF05) show the settling rate – and hence the thickness of the dust layer – depends on grain size. Since the gap criterion depends on the disk scale height, this would suggest that it is easier to create and sustain a gap in the dust layer than in the gas.

There are a variety of observational signature of planetary gaps, including mid-infrared dips (e.g. Calvet et al. 2002) Rice et al. 2003) and direct scattered light (Weinberger et al. 1999 [Schneider et al. 2006] and sub-millimetre observations of protoplanetary disks (Ozernoy et al. 2000 [Wilner et al. 2002]).

Recent models have indicated that ALMA will be able to detect planetary gaps at sub-millimetre wavelengths to distances of 100 pc (Wolf & D’Angelo 2005 Varnière et al. 2006). However, these models assume that the gas and dust are well-mixed within the disk and yet we know the dust-to-gas ratio changes substan-
tially as grains settle to the mid-plane and migrate radially (BF05). As well as the gas-to-dust ratio varying throughout the disk, we expect that the effects of planetary gaps will be stronger in the dust phase than in the gas phase, which will further affect observations.

In this paper we study the formation of a gap triggered by an embedded planet in the dust layer of a protoplanetary disk. We will study the effects of planet mass and grain size on gap formation and evolution in 3D dusty-gas protoplanetary disks.

2 Code description and simulation parameters

We use our 3D, two-phase (gas+dust), locally isothermal, non-self-gravitating code based on the Smoothed Particles Hydrodynamics (SPH) algorithm. The dusty gas is approximated by two inter-penetrating flows that interact by aerodynamic drag. For the nebula parameters used in this study, we are in the Epstein drag regime and hence

\[ F_D = \frac{4\pi}{3} \rho g s^2 v c, \]

where \( \rho \) is the gas density, \( s \) is the (spherical) grain radius, \( c \) is the sound speed, and \( v \) is the velocity difference between dust and gas. For details of how the equations of motion and the density of the two fluids are calculated, we refer the reader to BF05.

The dust particles are incompressible (\( \rho_d = \) constant) and there is no grain evaporation or coagulation, nor any gas condensation. All simulations presented consider just one (spherical) grain size at a time.

We set up a disk of gas and dust with a total mass of \( M_{\text{disk}} \) around a 1\( M_\odot \) star with an embedded planet of mass \( M_p \) at a distance of \( r_p \). The dust phase is 1\% of the total disk mass and the system is evolved for about 100 planetary orbits. The disk equation of state is isothermal with constant vertical temperature and radial profile \( T \propto r^{-1} \). Code units are set by \( G = M_\star = r_p = 1 \) and the isothermal sound speed at \( r = 1 \) is \( c = H/r = 0.05 \). The initial density profile is constant and the dust density is \( \rho_d \) (see below for details). The planet is treated as a point mass particle which moves under the gravitational influence of the star on a fixed circular orbit (i.e. no migration).

Simulations start with 50,000 gas and 50,000 dust particles. Particles are removed from the simulations if they cross the Hill radius of the planet, get closer than 0.4 code units of the central star (which sets the inner disk edge), or if they escape past 4 code units (which sets the outer disk edge).

In this work we present the results of two different disk models: (1) a small, low mass disk close to the minimum mass solar nebula (MMSN model), and (2) a classical T Tauri star disk (CTTS model). The MMSN disk has a mass of 2.9 \( 10^{-3} M_\odot \) and extends from 2 AU to 20 AU. The standard MMSN model has a 1 Jupiter mass \( (M_{\text{Jup}}) \) planet on a circular orbit of radius 5.2 AU in a disk containing grains 1 mm in size and \( \rho_d = 1.25 \) g cm\(^{-3} \). The CTTS disk mass is 0.01 \( M_\odot \) and spans 16 AU to 150 AU in radius. The standard CTTS model has a 5 \( M_{\text{Jup}} \) planet on a circular orbit of radius 40 AU in a disk containing grains 1 mm in size and \( \rho_d = 1.0 \) g cm\(^{-3} \).

For both disks we start by running the standard model and compare the evolution of the gap in the gas and dust phases. We then run a series of experiments to study the effect of grain size in the dust disk for both models, with \( s = 1 \) cm, 10 cm and 1 m for the MMSN disk and \( s = 100 \) \( \mu \)m, 1 mm and 1 cm for the CTTS disk. (Because the nebula conditions and particularly the density in the CTTS and MMSN models are different, the grain sizes used in the two models are different in order to obtain similar values for the gas drag and hence dust settling and migration rates.) This is followed by a series of experiments that study the effects of planetary mass on gap formation and evolution, with \( M_p = 0.05, 0.1, 0.2, 0.5 \) and 1.0 \( M_{\text{Jup}} \) for the MMSN model and \( M_p = 0.1, 0.5, 1.0 \) and 5.0 \( M_{\text{Jup}} \) for the CTTS model.

3 Simulation results

The results of the standard MMSN model is shown in Fig. 1. The left panel shows the top-down \((x, y)\) and side-on \((r, z)\) view of the gas and dust disk morphologies. While the planet opens a gap in the gas, the gap in the dust layer is much more striking. The right panel of Fig. 1 compares the evolution of the azimuthally averaged surface density profile of the gas and dust after 8.4 and 104 planetary orbits.

Recent observations have suggested that massive planets at large distances from the star may exist, such as a 5 \( M_{\text{Jup}} \) planet 30 AU from LkCa 15 (Pietuet al. 2006) and a 12.5 \( M_{\text{Jup}} \) planet 135 AU from GG Tau (Beust & Dutrey 2005). Our standard CTTS model has a 5 \( M_{\text{Jup}} \) planet at 40 AU and the results are shown in Fig. 2. For the nebular parameters used, such a massive planet almost completely empties the inner disk of both gas and dust (though this is likely due to the large inner disk radius - see Crida & Morbidelli 2007).

3.1 Effect of grain size

Since the gap criterion is partially governed by the disk scale height, and the dust scale height varies with grain
size, we ran a series of simulations to determine the effect of grain size on the gap. Three grain sizes are tested in both disk models: 1 cm, 10 cm and 1 m for the MMSN disk and 100 µm, 1 mm and 1 cm for the CTTS disk.

Fig. 3 shows how the gap morphology of both the MMSN and CTTS disks vary with dust grains size. We find that both the width and depth of the gap increases with increasing grain size.

3.2 Effect of planetary mass

Finally we investigate the effect of the planetary mass on the evolution of the gap. For our MMSN disk with 1 m grains, $M_p$ varies from 0.05 $M_{\text{Jup}}$ to 1 $M_{\text{Jup}}$, and for our CTTS disk containing 1 mm grains, $M_p$ varies from 0.1, 0.5, 1 to 5 $M_{\text{Jup}}$. Fig. 4 shows the comparison of the surface density profiles for both models. For the MMSN disk, the gap is more striking in the dust than the gas, while in the CTTS disk the inner disk appears depleted of both gas and dust, while the dust pile-up at the outer gap edge is clearly seen. For the CTTS disk, no change is seen in the surface density for a 0.1 $M_{\text{Jup}}$ planet in either the gas or dust phase. These results are in general agreement with the minimum planet mass required to produce a gap in the disk models of Paardekooper & Mellema (2006).

4 Discussion and conclusions

Structures created by planets in dusty disks are more diverse than those created in the gaseous disks. With only aerodynamic drag, we find that it is possible to create disks with a large central hole or a ring. Rice et al. (2006) also found that the presence of a planet can produce disks with a central hole for certain grain sizes.

Our results have implications for observational predictions of protoplanetary disks hosting planets. Wolf & D’Angelo (2005) and Varnière et al. (2006) use results of 2D hydrodynamic simulations to produce synthetic images of protoplanetary disks, but these simulations assume that the gas and dust are well mixed, which our results clearly demonstrate is not the case.

Because our general findings show than the gap is generally more striking in the dust disk, we suggest that predictions of observations of protoplanetary disks are too pessimistic. Our results show that the density contrast around the gap can be very strong (and the volume density can actually be greater than the gas volume density) and this would be detectable with ALMA. Our simulations support the results of Varnière et al. (2006), as we clearly see density enhancements in the outer gap edge of the CTTS simulations, even for the smaller grains sizes which would be responsible for the majority of the sub-mm and mm emission. Our results also support the predictions of Paardekooper & Mellema (2006) that gaps created by 0.05$M_{\text{Jup}}$ planets...
in MMSN disks should be visible with ALMA. For a more detailed analysis, we refer the reader to Fouchet et al. (2007).

While we see a clear density increase in the vicinity of the external 3:2 resonance of our standard MMSN disk, we do not believe that particles are trapped in the resonance. Plotting the dust eccentricity against semi-major axis when drag was neglected clearly shows resonances as thin vertical lines and a V-shaped pattern at the edges of the gap. However when drag is included, we find that the drag efficiently damps high eccentricities and the resonant signatures disappear. Furthermore, while the dust pile up appears to coincide with the 3:2 external resonance for the MMSN disk (when gas drag is included), this is not true for the standard CTTS disk – see Fig. 2. Thus the accumulation of dust that we and other authors (Paardekooper & Mellema 2006; Alexander & Armitage 2007) notice close to the outer gap edge is not due to resonant trapping. The accumulation of grains at the external edge of the gap may, however, favour the growth of planetesimals in this high density region.

We have conducted a series of 3D numerical simulations of two-phase (dust+gas) protoplanetary disks to study the behaviour of the dust in the presence of a planet. We ran a series of experiments with a minimum mass solar nebula disk as well as a larger, more massive Classical T Tauri star disk, varying the grain size and the planet mass. We find that gap formation is more rapid and striking in the dust layer than in the gas layer. Varying the grain size alone results in a variety of different structures, and for the CTTS disk these differences will be detectable with ALMA. For low mass planets in our MMSN disk, a gap was found to open in the dust layer while not in the gas layer. Simulations like these can be used to help interpret observations to
constraint the planet mass and grain sizes in protoplanetary disks.

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Fig. 4.— Azimuthally averaged surface density profiles for various planet masses after 104 planetary orbits. Top row: MMSN disk, Bottom row: CTTS disk. Left frames: dust profiles, Right frames: gas profiles.