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PROTOPLANETARY DISKS IN THE (SUB)MILLIMETER: PAVING THE ROAD TO ALMA

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Abstract. ALMA (Atacama Large Millimeter/submillimeter Array) holds the promise of revolutionizing our view of the Universe and in particular that of the planet formation process via unprecedented observations of protoplanetary disks. Preparing for its arrival is of utmost importance to ensure an optimal exploitation of its capabilities. In that view, we are following two roads. First, we are undertaking a observing campaign at millimeter wavelengths of southern disks with ATCA (Autralia Telescope Compact Array) to complement our existing multi-wavelength, multi-technique data and accurately model these sources to prepare followup observations with ALMA. Second, we numerically model the evolution of dust in the presence of an embedded planet in a typical Classical T Tauri star (CTTS) disk. We find that a system with a given stellar, disk and planetary mass will have a completely different appearance depending on the grain size and that such differences will be detectable in the millimeter domain with ALMA. Dust accumulates at the edges of the planetary gap where its density exceeds that of the gas phase, gap edges therefore appear as potential sites for the formation of additional planets.

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

1 Introduction

Following the discovery of the first planet around a solar-type star, 51 Peg (Mayor & Queloz 1995), and the subsequent search for exoplanets, with 493 detected to date*, the field of planet formation has been blooming in recent years. In this context, protoplanetary disks have been extensively studied, but a number of unknowns remain.

The ANR-funded "Dust disks" consortium (PI: F. Ménard, LAOG, co-PIs: J.-F. Gonzalez, CRAL, and S. Charnoz, CEA Sacaly) aims at bringing answers to some fundamental questions about protoplanetary disks: what is their structure? Can one reproduce all their observables with a single model? Are their masses and densities sufficient to form planets? Where and how do grains grow in disks to form planets? On what timescales? To that end, three axes are developped: (i) the acquisition of multi-wavelengths and multi-technique (imaging, polarimetry, spectroscopy, interferometry) data for a sample of disks and their interpretation in the framework of a single model per source, (ii) the analysis of these models to infer the disk properties as a function of their environment (stellar mass, age, ...) and derive the dust evolution (migration, settling, growth) signatures, and (iii) the numerical simulation of these disks with hydrodynamical codes to compute the formation of planets from realistic initial conditions and to obtain the signatures left by the presence of planets to predict the observables that upcoming instruments, such as ALMA, will have access to. One of the recent results is the modelling of the complex structure of the disk of HD 100546 by a tenuous inner disk, a gap from 4 to 13 AU, and a massive outer disk (Benisty et al. 2010).

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The evolution of the gas component of these disks is currently being investigated by the “GASPS” (Gas in Protoplanetary Disks, PI: B. Dent, ALMA Chile) Open-Time Key Program for the Herschel Space Observatory. It adresses the fundamental questions of the timescales of the gas evolution as well as the radiative interactions between gas and dust. It will survey a total of 250 disks with the PACS instrument, observing key tracers: lines (notably O I at 63 μm) and photometry. It will provide a statistical study of the combined evolution of gas and dust from young disks to debris disks, associated with a modelling effort using a grid of 300,000 models. Among its first results, the modelling of the dust component of HD 169142 has given constraints on the disk structure, with a gap at 10 AU, and on the fraction of PAHs, while that of the gas has shown a weak UV excess, that the main heating source is the PAHs, and has constrained the gas-to-dust ratio to 20–50 (Meeus et al. 2010).

2 Millimeter interferometry with ATCA

To complement the data sample covering visible to submillimeter wavelengths obtained in the “Dusty Disks” and “GASPS” programs and prepare future observations with ALMA, we have started an initiative to obtain additional data at larger wavelengths, in the millimetric range, that are sensitive to coalesced grains. This allows to obtain a reliable tracer of the grain growth process, precursor of planet formation. A striking example is that of the disk of HD 97048 which shows at 450 μm a flux that is 10 times larger than that expected from models based on shorter-wavelength data.

ATCA (Australia Telescope Compact Array), an interferometer comprising six 22 m-antennas which covers wavelengths from 3 mm to 20 cm with baselines of up to 6 km, is ideally suited for a followup of the sources we have been observing. Located in the southern hemisphere, it allows to observe disks that are inaccessible to the PdBI in the French Alps or the SMA in Hawaii. ATCA is therefore a precious asset to prepare the observations and modelling of a large number of disks: a good prior knowledge of the sources will be essential to secure followup observations with ALMA and complement the wavelength and $u-v$ coverages.

We have started an observing campaign with ATCA, with two components: the first is a mapping program of protoplanetary disks in the millimeter to complement the set of multi-wavelenght data already obtained by the consortium and better constrain the models for each source, and in particular grain growth. The second is a debris disk observation program at 3 mm, aiming at constraining the location of millimeter grains, which are the main contributors to the disk mass, and to break the degeneracy between mass, temperature and opacity. The morphology of the dust population can also trace the presence of planets, thus yielding constraints to their formation process at a later stage than observations of protoplanetary disks. We have obtained observing time in two runs in May and September 2010, the data is currently begin reduced. Figure 1 shows an example of the capabilities of ATCA on the disk of β Pic.

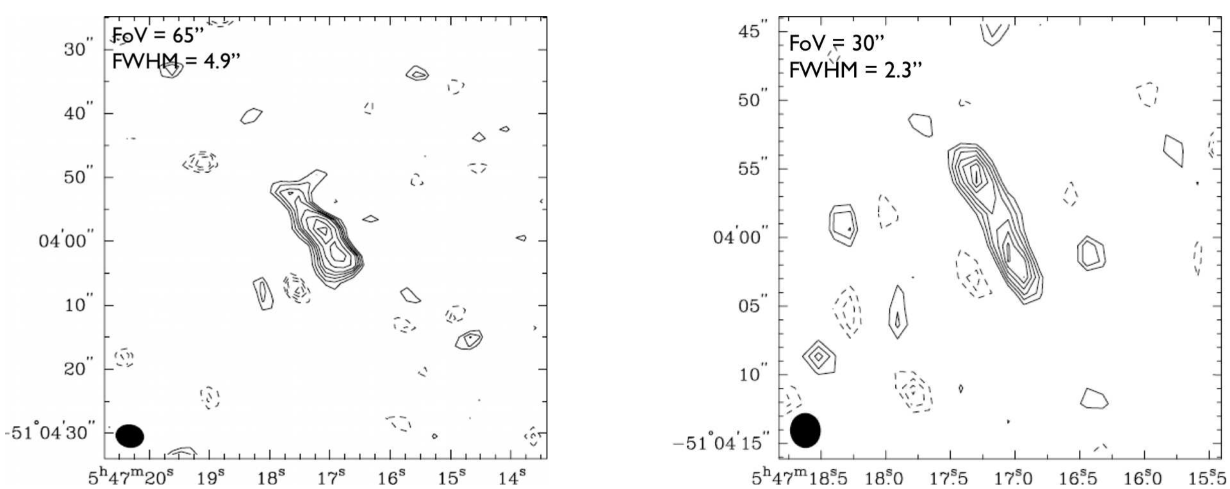

Fig. 1. ATCA contours of the β Pic disk. **Left**: 3 mm map (93+95 GHz). **Right**: 7 mm map (43+45 GHz).

3 Planet gaps in the dust layer of protoplanetary disks

Gaps carved by planets in gas disks have been well studied theoretically and numerically (see Papaloizou et al. 2007, for a review). More recent work (Paardekooper & Mellema 2006; Fouchet et al. 2007) has shown that gaps are more pronounced in the dust layer of a Minimum Mass Solar Nebula (MMSN) disk. Here we study the formation of gaps in dusty CTTS disks, motivated by their observability with ALMA which has been shown by (Wolf & D'Angelo 2005) assuming perfect mixing of gas and dust. We consider dust grains in the size range where gas drag has the strongest effect on their dynamics and which ALMA will be able to detect.

We use our 3D, two-phase (gas+dust), non self-gravitating, locally isothermal smoothed particle hydrodynamics (SPH) code (Barrière-Fouchet et al. 2005) to model the evolution of dust grains under the influence of gas drag in the Epstein regime. Our standard disk orbits a 1 $M_\odot$ star, has a mass $M_{\rm disk} = 0.02\ M_\odot$ and a viscosity $\alpha \simeq 0.01$, and extends from 4 to 160 AU. It contains 1% of 1 mm-sized dust grains by mass and a 5 $M_{\rm J}$ planet at 40 AU. The simulations include 400,000 SPH particles and are evolved for 100 planet orbits ($\sim 26,000$ yr). We vary the grain size s (100 μm to 10 cm) and planet mass $M_{\rm p}$ (0.1 to 5 $M_{\rm J}$).

Our previous work on planet-less disks (Barrière-Fouchet et al. 2005) showed that tiny grains are coupled to the gas and follow its evolution, while large grains are decoupled and follow their own orbits. For intermediate sizes around $s_{\rm opt}$ (optimal size depending on the nebula parameters, 1 mm-1 cm for our CTTS disk), gas drag is most efficient and grains settle to the midplane and migrate radially.

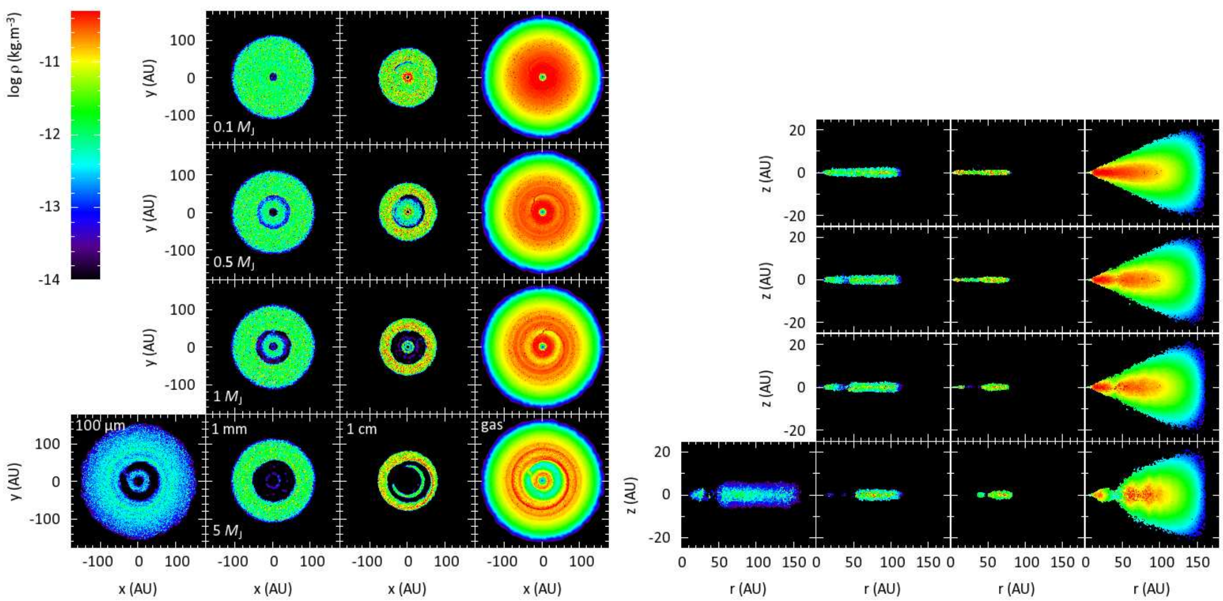

Fig. 2. Density maps in midplane (left panel) and meridian plane (right panel) cuts of the disks. The three leftmost columns show the dust density for $s = 100\ \mu$m, 1 mm and 1 cm, from left to right, and the right hand column shows the gas density. The rows show simulations with $M_{\rm p} = 0.1$, 0.5, 1 and 5 $M_{\rm J}$, from top to bottom.

Gap opening depends on the disk scale height H (Crida et al. 2006) and is easier in the settled dust layer than in the flared gas disk, as seen in Fig. 2. Gaps are deeper and wider for (1) larger grains (with smaller H) and (2) more massive planets. Larger planet masses are required to open a gap in the gas phase than in the dust. While a 0.5 $M_{\rm J}$ planet only slightly affects the gas phase, it carves a deep gap in the dust. Grains can be seen trapped in corotation only for the most massive 5 $M_{\rm J}$ planet (see Fouchet et al. 2010, for details).

4 Observability of planet gaps with ALMA

Wolf & D'Angelo (2005) showed that gaps carved by 1 $M_{\rm J}$ planets should be detectable by ALMA up to 100 pc. However, they used 2D simulations of a planet in a gas disk and assumed that dust grains were perfectly mixed with the gas before performing 3D radiative transfer calculations to obtain synthetic images at the shortest ALMA wavelength (350 μm) and therefore the highest spatial resolution.

We use the dust distributions obtained from our 3D SPH simulations for each grain size as an input to the 3D radiative transfer code MCFOST (Pinte et al. 2006) to compute synthetic scattered light images at several ALMA wavelengths. We reconstruct a grain size distribution described by a power law of index -3.5. Outside the size range of our SPH simulations, small grains are assumed to be perfectly coupled to the gas and large grains are omitted because their contribution to scattered light at those wavelengths is negligible. We also compute images assuming grains of all sizes follow the gas in order to highlight the important effect of gas drag. The resulting synthetic images are then passed on to the CASA simulator for ALMA and are shown in Fig. 3 for array configuration 20 (longest baseline $\sim$ 4 km). They reproduce the decreasing spatial resolution as wavelength increases.

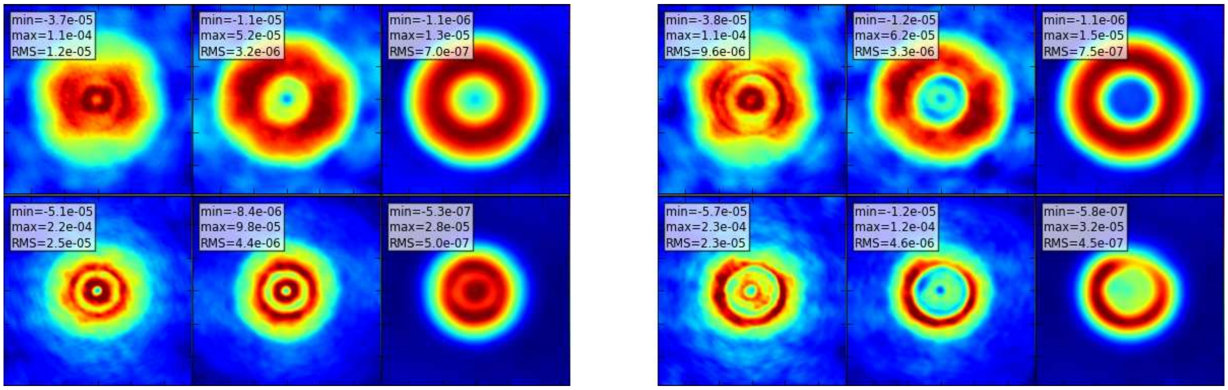

Fig. 3. ALMA synthetic images of the CTTS disk with a 1 $M_{\rm J}$ (left pannel) and 5 $M_{\rm J}$ (right pannel) planet for $\lambda = 850$, 1300 and 2700 μm, from left to right, for array configuration 20 (longest baseline $\sim$ 4 km). **Top**: naïve well-mixed assumption. **Bottom**: self-consistently included aerodynamic drag.

The images from the realistic case with aerodynamic drag (bottom row of Figs. 3 and 4) display notable features. The extent of the disk varies with wavelength, reflecting the location of different grain sizes in the disk (as grains with sizes closest to the wavelength contribute the most). The disk asymmetry caused by the spiral wave in the 5 $M_{\rm J}$ planet case is clearly visible and can provide a constraint on the angular position of the planet. Finally, the gap has a much higher contrast in the realistic case than in the naïve mixed case: it is deeper and its edges are denser and brighter. Even for the 1 $M_{\rm J}$ planet, it is still visible at the lowest resolution, whereas the naïve mixed case would only show a central hole. Gaps carved by lighter planets will therefore be much easier to detect than anticipated.

5 Conclusions

To prepare future observations with ALMA and identify the optimal setup, we observe southern protoplanetary disks with the ATCA interferometer at longer wavelengths, and thus constrain the source models. In parallel, we numerically model planet gaps in dusty disks and find that they are more striking and require a smaller planet mass to form in the dust phase than in the gas. They are wider and deeper for larger grains, both in MMSN (Fouchet et al. 2007) and in CTTS (Fouchet et al. 2010) disks. The variety of structures seen for different s and $M_{\rm p}$ are visible in the synthetic images and future ALMA observations will be able to constrain both parameters. Gaps will be detectable for lighter planets than anticipated.

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