SF2A 2009
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PROTOPLANETARY DISKS AND PLANET FORMATION

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Abstract. With more than 300 exoplanets discovered, the understanding of their formation has become central. But this formation is tightly linked to their environment, the protoplanetary disk which, itself, is a byproduct of stellar formation. I will thus quickly present the stellar formation scenarii (observational constraints, turbulence versus ambipolar diffusion). Then, I will come to our knowledge of disks (observations, models of irradiated disks, passive/active, flat/flared). I will describe the evolution of solids which are the building blocks for protoplanetary cores (radial migration, vertical settling and growth). I will then show synthetic images that can be produced with a self consistent treatment of dust in order to prepare for the ALMA observations. I will mention the Heidelberg scenario for rapid planetesimals formation. I will then sum up the state of our knowledge on planet migration which is an essential process to form giant planets before the disk has disappeared in the frame of the core accretion scenario. This will lead me to the actual models for core accretion and the central role of the disk on those and I'll finally quickly mention the other giant planet formation scenario: the gravitational instability.

1 Introduction

Protoplanetary disks are the birthplaces for planets, and as such, their physical properties must be understood in order to build a consistent scenario for planet formation. Disks mass amount to 1 to 10% of the mass of the central star. They are made of gas and dust with the dust component representing 1 to 2% of the disk mass. The dust phase is made of silicates, ices and PAHs (Polycyclic Aromatic Hydrocarbons). In simple models, the temperature profile goes as $T \sim r^{-q}$ with $1/2 < q < 3/4$ and the surface density profile as $\Sigma \sim r^{-p}$ with $1/2 < p < 2$ where r is the distance to the star.

Disks harbor a wealth of physical processes. In the gas phase, temperature is defined by viscous heating and irradiation while the velocity field is set by gravity and some turbulence. In the dust phase, we want to understand how dust grows or gets shattered during collisions. Gas-dust interactions occur through aerodynamic drag leading to vertical settling and radial migration (Weidenschilling 1977). Finally, disk-planet interactions are characterized by core formation from planetesimals, then runaway gas accretion and together with planet migration under the effect of disk gravitational torques.

2 Disk structure

2.1 Temperature structure in the disk

Disks can be flat or flared or, even, self-shadowed (Dullemond & Dominic 2004). If they are flat, it means that H, the vertical scaleheight goes as $H \sim r$. In that case as in the self-shadowed one (where $H \sim r^{\sigma}$ with $\sigma < 1$), the outer disk doesn't get direct stellar light and is cooler than in the flared case (where $\sigma > 1$) where the outer disk can get direct stellar light. These issues were recognized a long time ago (Kenyon & Hartmann 1987) and the flared structure helped explain observed SEDs (Spectral Energy Distribution). Another level of refinement was to add a puffed up inner rim (because the inner part of the disk is directly heated by the star) and help reproduce SEDs even better (Dullemond et al. 2001). Now, different methods are used to provide a reasonable temperature structure for the disk: 3D codes with full radiative transfer (see the benchmark for a few of them done by Pinte et al. 2009) or 1+1D axisymmetric approximations where the vertical structure is computed independently of the radial one. The choice depends on the the level of accuracy needed and on the time available for computation.

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2.2 Turbulence

The best candidate as source for turbulence is the MRI (Magneto-Rotational Instability) as was shown by Balbus & Hawley (1991), although it is not clear that the ionization fraction in the midplane is high enough for MRI to be sustained there. Only full 3D, local or global, simulations can allow to characterize this kind of turbulence and they are tremendously numerically demanding. Therefore, when the characterization of turbulence is not the main topic, people often revert to the "alpha" formalism (Shakura & Sunyaev 1973) where turbulence is described as some sort of viscosity with $\nu = \alpha c_s H$ where c_s is the soundspeed.

3 Dust phase

3.1 Dynamics

Dust dynamics is influenced by the disk structure and, reversely, dust acts on the temperature structure of the disk. The opacity is dominated by small grains and will vary according to the spatial and size distribution of the grains. In the disk, gas is supported against gravity by a pressure gradient. Therefore, its velocity field is slightly subkeplerian. On the opposite, the dust phase has no internal pressure and needs to flow at a keplerian speed in order to compensate for the stellar gravity. As a result, dust feels a headwind and looses angular momentum. This is why it settles to the midplane of the disk and spirals inward towards the star. To be more precise, dust will always accumulate in pressure maxima (Haghighipour & Boss 2003). The pace at which these movements occur depend on the the grain size. Small grains are strongly coupled to the gas and will follow its motion, intermediate size grains are partly decoupled and will settle and migrate most efficiently, large grains will almost not feel the gas and follow perturbed keplerian orbits. In a MMSN (minimum mass solar nebula, see Hayashi 1981), the faster radial migration occurs for 1 m size boulders, while in a CTTS (Classical T Tauri Star) it will rather be 1 cm.

3.2 Observations

In the Infrared, observations can be analyzed with models where gas and dust is well mixed, because we observe grains that are small enough to be strongly coupled to the gas. But, in the case of ALMA observations, the problem is different. Disks will be observed in the millimeter wavelength, i.e., we will observe mm size pebbles. Their dynamics and subsequent spatial distribution is substantially different to that of the gas. Grains have to be self-consistently followed together with the gaseous evolution.

Especially, we investigate the visibility of a gap in the dust layer of a CTTS disk created by a 5 Jupiter mass planet at 40 AU from its parent star (Fouchet et al. 2009a,b). We first ran SPH (Smooth Particle Hydrodynamics) 2-fluid simulations in order to derive the spatial distribution of dust in the case where a planet is embedded in the disk. Then we fed these results into the radiative transfer code MCFost and show that the appearance of the disk is substantially different if we consider dust as well mixed or if we self-consistently compute its spatial distribution (see Fig. 1).

3.3 Growth

Beside dynamics, growth and shattering of dust will also affect the disk structure. Growth occurs upon collisions until 1 to 10 cm through Van Der Waals forces. Collisions occur because of the existence of velocity dispersion due to brownian motion for the smaller particles, gas drag for the slightly larger ones and turbulence for all of them. This initial phase of dust growth has been investigated by Laibe et al. (2008) while neglecting shattering. They show that growth occurs without migration during the settling phase, then migration occurs faster than growth, and then, once grains are large enough to decouple from the gas, they grow without migrating. As a result, a plateau appears in the size distribution at the level of the faster migrating grains. Beyond the 10 cm size, collisions become rather destructive. It is yet unclear how to go from 10 cm boulders to 1 km size planetesimals for which gravity will take over and growth will proceed.

Johansen et al. (2007) then propose a scenario to jump directly from 10 cm rocks to planetesimals. They run simulations where self-gravity and magnetic fields are included. They have two fluids, gas and dust and they also include the back-reaction of dust on gas (often neglected). They can show how streaming instability first, then MRI and/or Kelvin-Helmholz instability can concentrate dust into transient vortices. These vortices

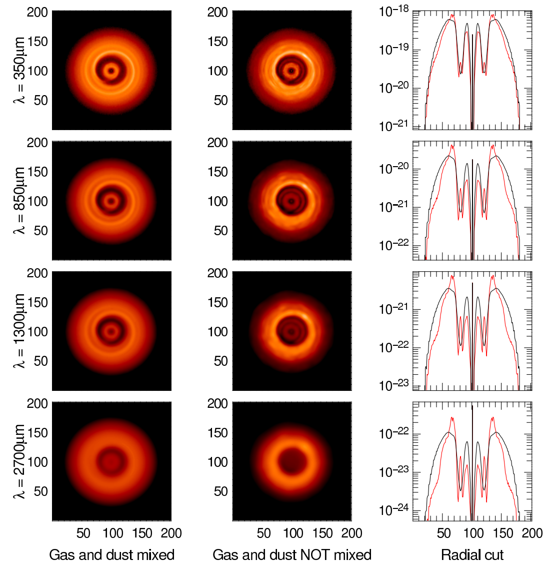

Fig. 1. Synthetic images of the disk at different wavelengths in the well mixed (left) and non well mixed (center) cases. Brightness profiles (right)

leave long enough for dust to accumulate up to a mass where self-gravity will take over and keep the structure together.

3.4 Open questions

A lot of questions remain concerning dust. How is crystalline dust transported to large radii where it is observed? Is it simply due to the viscous spreading of the disk (Dullemond et al. 2006; Ciesla 2009). What is the timescale for grains growth? Millimeter grains are observed in class 0 stars, but, at the same time, smaller grains are observed in older disks. What is the timescale for planetesimals formation? How do planetesimals form? Through coagulation? Is it a global instability in the dust layer? Is it local fragmentation in density enhancements in the dust phase due to turbulence (c.f. Johansen et al. 2007)?

4 Planet migration

While the planet forms, it migrated already. There are different regimes of migration but they share the same issue that they are all too fast for planets to survive without being eaten by the star. Fortunately, potential solutions are under study to slow down migration. Type I migration: Small planets (less than a few Earth Masses) do not strongly affect the disk (they do not create a gap). The linear theory (Goldreich & Tremaine 1980) is often used but insufficient. Yet recent works show that it is sensitively dependent on thermodynamics and that migration happens at a slower pace if we better model the radiative transfer (Paardekooper & Mellema 2006, 2008). Type I migration may also be slower when turbulence is included because the planets achieve a random walk through the disk (Nelson 2005). Type II migration: Large planets (more than a Jupiter mass) open a gap in the disk. Here, the linear theory is inadequate. If the gap is very deep and clean, migration will occur on the viscous timescale. Otherwise, it will depend on thermodynamics (Fouchet & Mayer 2009c), viscosity etc... Type III migration: Intermediate planets can enter a runaway migration which is very fast but can be directed outwards for a small period (Masset & Papaloizou 2003).

In all cases, physical ingredients are often neglected because of the difficulty to evolve the simulations if they are properly included. This is the case for self-gravity, thermodynamics and turbulence. Also, the importance of corotation torques and of the circumplanetary material get recognized (Crida et al. 2009). At the moment, there is no general picture and it is becoming very challenging numerically but a huge effort is invested in solving this problem and answers are coming.

5 Core accretion and gravitational instability

All the previous ingredients are included in a single model, the core accretion model. This was devised by Pollack et al. (1996). They had a steady disk, a model for core formation from a subearth core and planetesimals getting accreted and a detailed model for the planet envelop and the gas accretion. But the timescale to build a Jupiter was longer than the lifetime of a disk (less than 10 millions of years from observations). Alibert et al. (2005) found a solution to this issue by accounting for the migration of the forming core. This allowed the core to meet more planetesimals in its feeding zone and to grow faster. Such a model relies on a prescription for the migration rate of the planet and progress in this domain will improve this model. Mordasini et al. (2009a,b) then produced a giant planet population synthesis which reproduces well the planet observations.

Now, in the Bern group, we improve the disk structure in order to match observations. Namely, we now include irradiation, making the outer parts of the disk warmer than in the previous models. As a result, the transition from type I to type II migration is delayed because the gap is more difficult to open in the warmer outer disk.

The other process to form planets is the gravitational instability. There, a direct collapse of a gaseous clump can lead to a giant planet without a core if the disk is massive and cold enough (Mayer et al. 2002). There is no need for a core and no problem with the too fast type I migration. The formation of a Jupiter mass planet is very rapid removing the issue of the short disk lifetime. Yet, this scenario is highly debated because there are uncertainties concerning the survival of clumps because of the shear in the disk. The simulations are very demanding and cannot follow hundredth of orbits. The thermodynamics is, here again, very important. It is not clear that the disk cools fast enough for the clump to collapse. The perspective at the moment is rather a hybrid model between core accretion and gravitational instability given that giant planets have been observed at such a large distance in the disk that they could never be formed in situ by core accretion (Boley 2009).

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