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Not so smooth after all: resolving dust and gas structures in protoplanetary disks

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English summary

Since the beginning of Human existence, mankind has wondered about its origin and place in the universe. Stars and constellations were the origin of countless legends and myths, and the names of some of them still carry the trace of them. Nobody today would think that those stories have actually happened, but they clearly highlight the intuition of people of all times that the answers to the questions about our origin and place in the universe can only come from the observation and study of the skies. As science progresses, the latter statement is still true. Telescopes are continuously being built around the world and sent to space, with the goal to be able to look better at those same skies and to answer those same questions. In particular, how did life begin?

In the greatness of the universe, there is only one place where we know for sure that life has originated: planet Earth. Until about 25 years ago, no planet was known outside of the solar system. In 1995, however, the first *exoplanet* was discovered, and since then more than 4000 new planets have been confirmed. This boost of discoveries opens a promising new path toward the understanding of the origin of life. In particular, understanding how planets form from the chemical and physical point of view is a critical field of study.

The path that leads from giant interstellar clouds, as the ones in Fig. 6.15, to planets is complicated and involves many different physical and processes at different scales (see Fig. 1.2). Many aspects of this path are therefore still not well understood. It is clear, however, that star and planet formation starts from giant molecular clouds. 99% of such clouds is made of molecular gas, while 1% is made of solid dust. Some clouds are gravitationally unstable: this means that their mass is too high to be supported by the pressure of the gas they are made of. Consequently, they start collapsing under the effect of their own gravity. During the collapse, they start rotating faster and faster due to conservation of angular momentum, until at some point the centrifugal force can actually prevent the material from further collapse and a disk-like structure is formed. These structures are called *protoplanetary disks*, as they are the cradle of planet

Figure 6.12: View of the dust component of the clouds in the Corona Australis star forming region. The denser clouds effectively block light from more distant background stars in the Milky Way. Image Credit & Copyright: Fabian Neyer.

formation.

Dust in protoplanetary disks can then grow from the size of tiny, sand grains to pebbles, boulders, and planetesimals, the building block of rocky planets and of the cores of giant gaseous planets. Once formed, planets interact with the rest of the material in the disks by carving gaps and cavities, creating rings and exciting waves.

Until abut 10 years ago such structures could not be observed from Earth, due to the spatial resolution of former-generation telescopes. It was like looking at a painting from far away: the large shapes can be seen, but the details are hidden and cannot be seen. Similarly, disks appeared smooth and symmetric. Moving closer to a painting, however, more details become clear, and when one is close enough even the single paintbrush strokes can be distinguished (e.g., see Fig. 6.16). What allowed us to "move closer" to protoplanetary disks are the unprecedented capabilities of a new powerful telescope: the Atacama Large Millimeter/submillimeter Array (ALMA). When observed with ALMA's full capabilities, disks are not smooth and symmetric anymore, but show many structures and a variety of morphologies, and even more than we would have expected.

Alongside ALMA, other telescopes and instruments, such as VLT/SPHERE and Gemini/GPI, have been built to look for planets embedded in protoplanetary disks. Interestingly and against expectations, only a handful have been detected to date.

The ubiquity of substructures combined with the lack of planet detections in protoplanetary disks are challenging the interpretation of substructures as

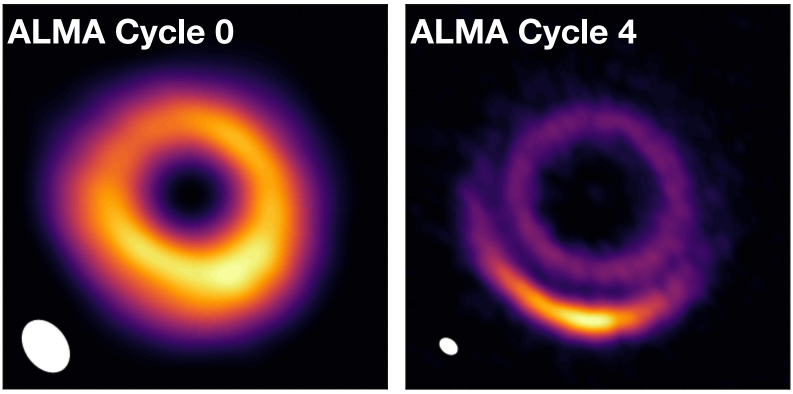

Figure 6.13: Images of the protoplanetary disk around HD 135344B taken at different resolutions. On the left, the very first ALMA observations at 0.″25 (∼ 30 au) resolution, apparently showing a slightly asymmetric ring. On the right, the more recent ALMA observations of the same object, reaching a spatial resolution of 0.″06 (∼ 8 au): at this resolution, more substructures can be distinguished, i. e. an inner, symmetric ring and an outer azimuthal asymmetry.

originating by the interaction between disk and planets. In particular, the questions that this Thesis will try to answer are the following:

- Can substructures in protoplanetary disks originate from other phenomena than planet-disk interaction?
- Which kind of information can substructures in protoplanetary disk provide about the physical properties of the disk?
- Are substructures in the gas related to those in the dust, or do they provide indipendent information?
- To what extent are disk properties due to evolution, rather than initial condition?

This thesis and future outlook

Chapter 1 of this thesis gives an overall introduction of the star and planet formation theory. The phases that lead from cloud to disk phase are explained, as well as the physical mechanism playing a role in dust growth and evolution. The telescopes and numerical tools employed in the analysis are also presented.

Chapter 2 presents a study of the structures in the disk surrounding GG Tau A. The peculiarity of this protoplanetary disk is that it is not rotating around a single star, but around a binary (it is therefore called *circumbinary* disk). The GG Tau A circumbinary disk shows a very narrow ring located at $\sim$ 200 au from the central stars. The region between the stars and the ring is completely devoid of dust and of most of the dust, as the material has been pushed out by the gravitational interaction with the stars. The interaction between the stellar companion and the disk is very similar to what would happen if a massive planet was present instead. Depending on the mass of the companion, however, the theoretical calculations predict a different ring locations. The position of the ring also depends on the orbit of the star. Running a set of hydrodynamical simulations and comparing the results with the observations of the disk and the stellar motion, we conclude that the stellar orbit that better fits into the observational constraints is an orbit misaligned with respect to the plane of the disk.

Chapter 3 and 4 focus on another specific object, namely HD 135344B (see Fig. 6.16). From the very first ALMA observations, the disk around HD 135344B appeared to be very interesting, with a large $\sim$ 50 au inner cavity and a dust ring similar to that of GG Tau A, but smaller, as expected if it was carved by a planet. Another difference with GG Tau A is the fact that the HD 135344B disk is not symmetric, but is brighter in the south. In addition, scattered light observation of the same disk, probing small grains, located in the surface layer of the disk, show bright, symmetric spiral arms, usually explained with two additional planets. Chapter 3 presents higher resolution ALMA observations of the disk, highlighted that what seemed to be an asymmetrical ring in earlier ALMA observations, rather appeared at higher resolution like a symmetric, inner ring and a separated outer banana-shaped asymmetry, which could be interpreted as a vortex. The tip of the spiral arms is very close to the center of the asymmetry (central panel if Fig. 3.1): we therefore propose that the spiral arms are being triggered by the vortex, rather than by additional planets. Only one planet, carving the inner ring, is required in this explanation. This is consistent with the fact that despite the efforts no planet has been yet identified in the outer regions of HD 135344B.

Chapter 4 presents observations of the disk around HD 135344B at even higher resolution and at a different wavelength: this time, the inner ring and the outer asymmetry are clearly distinguishable. Moreover, combining the new observations with the previous one, a multi-wavelength study of the vortex is carried out. This allows to constrain many properties of the dust grains inside the vortex. For example it is clear that grains are larger in the vortex than in the rest of the disk: it is therefore likely that the dust is growing there to larger sizes, possibly originating a population of planetesimals. The mass of the

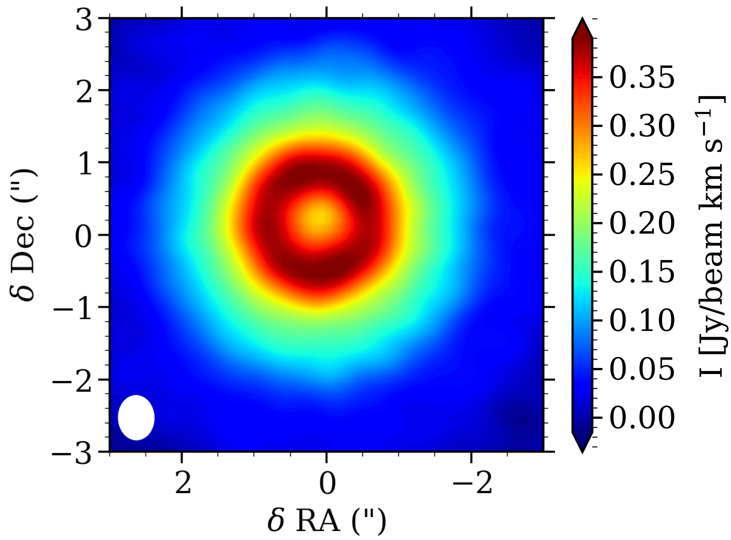

Figure 6.14: The ring shaped CN emission detected in the disk around TW Hya.

vortex is also measured, and found, within the uncertainties, to be consistent with the scenario of a spiral-launching vortex.

The first three chapters focus mostly on dust structures. Chapter 5 focuses on gas instead, and in particoualr on CN emission. Being one of the brightest lines in disks, CN is an interesting molecule to study. What makes it even more interesting is the fact that resolved observations of protoplanetary disks always show ring-like structures (see Fig. 6.17). Are these rings also due to a planet? Are they correlated with dust rings? In order to answer these questions, CN emission from a grid of models of protoplanetary disks was simulated using the DALI code. The conclusion is that CN always shows rings, even in structureless full disks. The origin of those rings is in fact chemical. The reaction leading to this peculiar emission, however, strongly depends on some properties of the disk, such as its flaring, radius, mass and the far Ultraviolet emission from the central star. When observing CN in protoplanetary disks, therefore, the ring size and brightness can potentially be used to constrain these properties.

Chapter 6, finally, focuses on the ALMA observations of dust and gas not only in single disks, but in many disks in a single star-forming region, Corona Australis (CrA), shown in Fig. 6.15. CrA is thought to be a young star-forming region, and as such is expected to show relatively large and bright disks as other regions of the same age such as Lupus. No disk is however detected in the gas, and the dust disks appears to be faint and small, comparable to those of a region 10 times older than Lupus, i.e. Upper Sco. New VLT/X-Shooter spectra of the targeted objects, however, seem to confirm their young age. The question about the origin of the low fluxes remains open, but two main options are possible: either two different star formation events occured in CrA, a few Myrs apart, or the disk brightness and size observed today are strongly affected by the initial conditions (such as the rotation of the core) in the very early phases of the star formation process. More observations are needed to distinguish the scenarios. In particular, if disks around the youngest objects in the region are observed and found to be fainter than usual, it would be clear that initial conditions play an important role by making the disks small and less massive from the very beginning.

To date, it remains unclear whether the observed structures are due to already formed planets or to some other physical mechanism. So far only one planet has been imaged in a disk, but future observations may directly image more embedded planets associated with these structures. In the meantime, new promising approaches to indirectly infer the presence of planets are becoming more and more common and will prove critical in the near future. The perturbations to the gas motions induced by planets, for example, has already been used in a few cases, and the same technique can now be applied to more systems. Emission from circumplanetary disks associated to embedded protoplanets as well as the emission associated with their accretion onto the planets have also recently been detected with ALMA and MUSE, respectively. Such observations may be more common in the future.

In the meantime, additional multi-wavelength studies of protoplanetary disks such as that carried out for HD 135344B can shed light on the dust properties inside dust traps, including inside vortices. In particular, the connection between vortices and spiral arms in scattered light should be better investigated in more systems, also exploiting the sensitivity and spatial resolution of ALMA at the higher frequencies.

These studies are critical to understand if substructures in disks are the birthplace of new planets. They will ultimately also tell whether and how the variety of structures observed at mm-wavelengths is linked to the diversity in the exoplanetary systems' properties, and ultimately, our origins.