Dusty perspectives on the cradles of planets
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English summary

We live in a small corner of our galaxy in the universe, the Milky Way, in a planetary system we call the Solar System. For a long time, we believed our system was the center of the universe, or more correctly, that humans were the center of the universe, a belief we now know is far from true. If we were born and raised here, it's not unreasonable to imagine that something similar could have happened around other stars in our galaxy or in distant galaxies.

Interestingly, the Sun is not even a typical star within the Milky Way, let alone the universe. In fact, recent evidence suggests that the formation of our Solar System might have followed a rather unusual path compared to most other planetary systems. Still, the mere fact that we know about these other possibilities, and that life may form elsewhere, continues to intrigue us. Then the question remains: What led to the formation of this specific planetary system around a solar-mass star that eventually enabled life to evolve? To find an answer to this, we must go back to the very beginnings, to the birth of stars and planets, in the vast void of the universe where gas and cold dust gather, the interstellar medium (ISM).

Star and Planet Formation in the ISM

In our universe, there are vast regions of gas and dust called molecular clouds that form the ISM. These are the places where stars and planets are born. Molecular clouds consist primarily of hydrogen and helium, with trace amounts of heavier elements like oxygen, nitrogen, and carbon.

When parts of these clouds become dense and massive enough, gravity causes them to collapse, forming a protostar. The collapsing material, both gas and dust, begins to heat up and flatten into a rotating structure as the protostar accretes. This leftover material, around the young protostar, forms what we call a protoplanetary disk.

Within this disk, dust particles begin to stick together, forming larger and larger clumps. Over time, these clumps become as large as kilometer-sized objects, planetesimals, which then continue to accrete more material and grow into planets. As the protostar evolves, nuclear fusion eventually ignites in its core. At that point, the surrounding disk starts to clear due to the strong radiation coming from the star and what remains are the planets and planetesimals, now part of a newly formed stellar system. This system can remain stable for millions or even billions of years, until the star exhausts its nuclear fuel. Depending on its mass, the star may then explode as a supernova or expand and leave behind a white dwarf. In either case, its remaining material is returned to the interstellar medium, restarting the cycle of star and planet formation. This is the star formation process, shown also in Figure 1. While we can look deep into Earth's past through meteorites and geological records, the best way to study planetary origins and the potential for life elsewhere is by observing other protoplanetary disks, systems still in the very early stages of planet formation. These systems exist within nearby molecular clouds and offer us a unique window into the beginning of planets like our own. To explore them, we rely on powerful telescopes capable of detecting the light emitted from either the dust particles or the atoms and molecules in these disks. In particular, interferometric telescopes, which allow us to resolve their structure in remarkable detail, helping us understand the environments where planets, and perhaps life, are born.

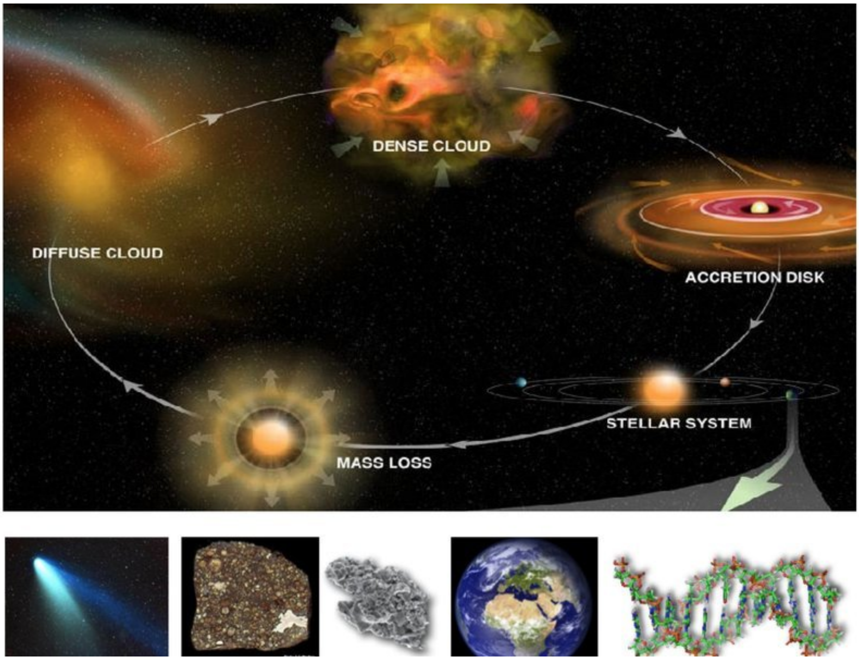

Figure 1: This image illustrates the full star formation process, together with the early stages of planet formation. It all begins with a molecular cloud, a cold and dense region of gas and dust in the interstellar medium. Over time, parts of this cloud collapse under gravity, forming a protostar surrounded by an accreting disk of material. As the protostar evolves, the surrounding protoplanetary disk becomes the birthplace of planets. Within this disk, small particles collide and stick together, forming dust grains and eventually planets. Over time, much of the disk material is cleared away, leaving behind a planetary system with complex organic molecules, atoms, and residual dust—remnants like planetesimals of the original disk. Image credit: B. Saxton, NRAO/AUI/NSF

Thesis overview

In this thesis, using the most modern telescopes, I have studied and investigated the properties of dust in nearby protostars and star-forming regions, which typically resemble the structure shown in Figure 2. My research has primarily focused on how dust evolves and grows, an essential step toward planet formation, but I have also explored how molecules, particularly complex organic ones, can contribute to answering fundamental questions about the origins of planetary systems.

The thesis is structured into five chapters. Chapter 1 provides an introduction to star formation, protoplanetary disks, the role of dust and gas in these disks, the presence of complex organic molecules, and substructures in (isolated) disks. The subsequent chapters present detailed analyses of dust evolution, dust growth and the chemistry of complex organic molecules across different star-forming regions.

Chapter 2: In this chapter, I investigate the high-resolution dust emission from the binary system NGC 1333 IRAS4A, a deeply embedded protostellar region, which represents one of the earliest stages of star formation. Studying such young systems is essential to understanding when and how planet formation begins. Specifically, this work explores whether the initial steps toward planet formation, such as grain growth or substructure formation, can already be detected at this early stage, or whether they occur much later in the protoplanetary disk evolution. The analysis of dust properties in IRAS4A1 reveals that the dust has already reached the necessary conditions, such as grain size and density, to support the formation of planetesimals or substructures, the latter being the regions where we believe planets begin to form. Furthermore, radiative transfer modeling suggests that substructures may already exist within the system, but remain hidden beneath dense layers of gas and dust. This finding implies that planet formation might begin much earlier than previously thought.

Chapter 3: In this chapter, I continue the investigation of the NGC 1333 IRAS4A system, this time focusing on the complex organic molecules (COMs) surrounding IRAS4A2, rather than the dust. I analyzed the spatial distribution of these molecules and explored their relationship with the dust grain distribution in the system. The results reveal that the radial and

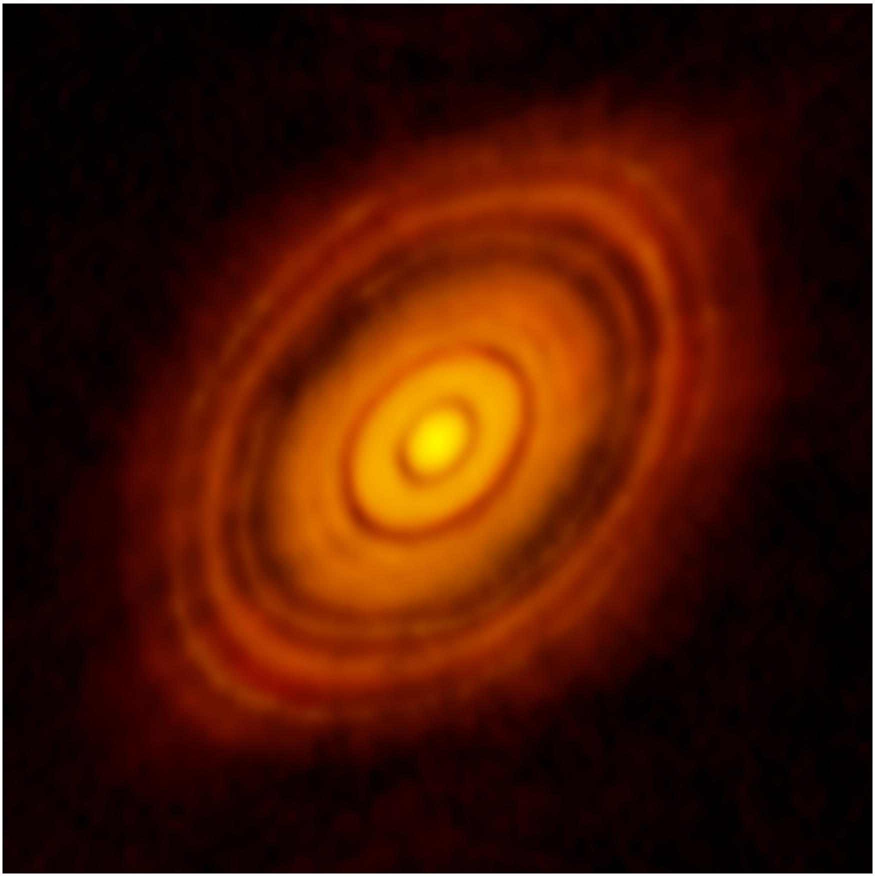

Figure 2: This image shows what a protostar with a protoplanetary disk looks like when observed with a telescope such as the Atacama Large Millimeter/submillimeter Array (ALMA) at submillimeter wavelengths. The disk reveals various features, including rings and gaps, which we refer to as substructures, these may be the result of planet formation or other dynamic processes within the disk. Image credit: ALMA(ESO/NAOJ/NRAO); C. Brogan, B. Saxton (NRAO/AUI/NSF)

azimuthal distribution of the complex organic molecules is significantly more intricate than previously expected. This complexity suggests a deeper connection between the molecular emission and the way dust is accumulating and beginning to settle in specific regions of the system.

These findings point toward a rapid dust evolution process in IRAS4A2, especially when compared to its primary binary companion, IRAS4A1, where most of the molecular emission appears to remain obscured beneath a thick layer of dust.

Chapter 4: In this chapter, we study a slightly more evolved protoplanetary disk: HL Tau. Using a multi-wavelength analysis approach, we analyzed high-resolution images of the disk taken at several different frequencies. By applying radiative transfer modeling, we were able to fit the observed emission and derive key dust properties, including dust grain size, dust density, and dust temperature. In particular, we utilized Band 9 observations from the ALMA telescope, which probe optically thick wavelengths. This allowed us to study the disk from a different perspective, revealing a structure distinct from that observed at longer wavelengths. The data likely trace smaller grains measurable at millimeter wavelengths and reveal a larger disk radius, denser substructures, and possibly a different vertical extent of the disk compared to previous observations. Additionally, we identified a previously undetected inner substructure visible only at these shorter wavelengths, along with a notable asymmetry in the disk.

Chapter 5: Chapter 5 focuses on understanding protoplanetary disks across an entire star-forming region. In this work, we studied and analyzed all known (isolated) disks in the Lupus region, examining their radii and other physical properties. Investigating a complete sample of protoplanetary disks offers valuable insights into dust evolution and its connection to planet formation. However, many previous studies have been limited by low-resolution observations, mainly due to telescope constraints. In contrast, our higher-resolution analysis revealed that over 67% of the disks in Lupus are very compact, with radial extents smaller than 30 au. Additionally, we discovered new substructures within several of these disks. These results suggest that the majority of protoplanetary disks already possess the conditions necessary to form one of the most common types of exoplanets: super-Earths. This connection between early disk properties and the observed exoplanet population provides important clues about the typical pathways of planet formation, helping bridge the gap between disk observations and planetary system outcomes.

Based on the individual results of all the chapters, we conclude that greater attention should be given to both the radial and vertical structures of protoplanetary disks. These disks are far more complex than previously thought, not simply large, flat structures, but systems with intricate geometries and a wide range of radial extents.

In particular, radial variations in the vertical structure of protoplanetary disks offer important insights into the initial conditions of planet formation, how this process is triggered, and how substructures, which may eventually give rise to planets, form within disks. Moreover, understanding whether compact or large protoplanetary disks are more common can help answer a key question: Is our Solar System the exception rather than the rule? If it is, then life might be rarer and harder to form than we've often assumed.