Protostellar jets and planet-forming disks: Witnessing the formation of Solar System analogues with interferometry

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English summary

How are stars and planets made?

The curiosity about the origin of the Earth, our planets and the Sun is a constant drive for new astronomical discoveries. Thus, it is no surprise that with each new achievement of technology – starting from a simple hand telescope invented by Lippershey and used by Galileo, to 8-m diameter Very Large Telescopes and 66 radio antennas of the Atacama Large Millimeter/submillimeter Array –we try to learn about our origins by staring into the sky. The discoveries over the past 30 years show that our Solar System is only one example of many planetary systems orbiting other stars, with more than 4000 planets discovered to date. To understand how such planets are made it is not sufficient to observe planets that are already born, but it is essential to point our telescopes to the stellar and planetary nurseries: molecular clouds.

Figure 1: *Left: Spitzer* composite image of NGC1333 star-forming region in Perseus molecular cloud. Colors correspond to different wavelengths of observations: 3.6 μm (blue), 4.5 μm (green), 5.8 μm (orange), 8.0 μm (red). Credit: NASA/JPL-Caltech/R. A. Gutermuth (Harvard-Smithsonian CfA). *Right:* Optical light image in blue, green, and red filters of the same region. Credit: Robert Franke.

In recent years plenty of evidence has emerged that planet formation takes place very fast on a cosmic time-scale. In this thesis, I provide evidence that planets must start to form already in the first 100 000 years after star formation begins, a blink of an eye compared to the age of our Sun – 4.6 billion years. This has important implications: to understand what affects planet formation and under which conditions planets are forming, we need to observe very young stars. The conditions in those systems are anything but calm and quiet: powerful supersonic jets are launched from the star and the disk, the temperature is high due to a lot of gas still infalling onto the disk, and the chemical composition of the gas is heavily affected by the range of conditions. An example of such a young star-forming region is the Perseus molecular cloud, with one of its most spectacular clouds NGC1333 presented in Fig. 1.

If we want to get to the bottom of the origin of complex organic and prebiotic molecules on Earth, we need to probe what happens in first 100 000 years of the star-formation cycle. This phase of stellar birth is called the protostellar stage and is the focus of this thesis.

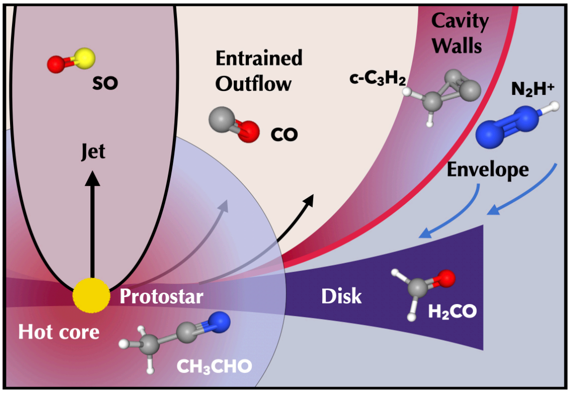

Figure 2: Cartoon illustrating the physical components of a protostellar system. Arrows indicate the direction of material in motion; the protostellar jet emerges from the innermost region of the system, but not exclusively from the protostar itself. Example molecules that are a good tracers of the corresponding components are presented. Molecule images from: https://pubchem.ncbi.nlm.nih.gov/.

Observations of young stars

Young stars are deeply embedded in the dusty clouds that they are made of. This means that optical telescopes, even the most powerful ones, are not well suited to observe them due to heavy extinction. Another factor that does not make observations any easier is that stellar nurseries are cold environments. The nature of light (electromagnetic waves) is such that our Sun with a surface temperature of 5400 K shines brightly in the visible range. On the other hand, radiation from protostellar systems can be characterized with temperatures of 30 − 500 K, which means they emit mostly at longer wavelengths than the Sun − in the infrared and submillimeter regime of the electromagnetic spectrum. This is why this thesis employs submillimeter and centimeter wavelength observatories, such as the Atacama Large Millimeter/submillimeter Array (ALMA) and Very Large Array (VLA). These interferometric facilities combine the signal from each of the separate antennas to achieve a resolution that is equivalent to that of a single-dish telescope with a diameter similar to the largest distance between the antennas.

Thermal emission from cold dust surrounding protostars is manifested by broad-band radiation across wavelengths. Spectroscopy, on the other hand, focuses on discrete peaks and troughs in light and is a unique tool to probe the chemistry and physics in such young regions. The submillimeter range is rich in molecular rotational lines, which inform about the abundances of molecules and energies that they contain. What is crucial, is that different molecules trace different physical conditions. Using this knowledge we can dissect a protostellar system and associate molecules with individual components (Fig. 2). This thesis uses continuum observations to probe thermal emission from small dust particles in protoplanetary disks and envelopes around young stars, and spectroscopy to trace gaseous molecules in different parts of protostellar systems.

Protostellar jets and disks

This thesis focuses on characterizing different components of protostellar systems, most notably their jets and disks. Jets consist of gas at high velocities (ranging from tens to hundreds kilometers per second) released from the inner regions of the protostellar system. As the cloud core collapses, the material spins faster due to the conservation of the angular momentum, and some excess of this rotational energy is released in high-velocity jets. Because the velocities at which the jet moves are highly supersonic, they create shocks with the surrounding medium, which means that the conditions such as density and temperature change dramatically. Jets are surrounded by slower and wider, low-velocity outflows, comprised predominantly of material that is entrained from the envelope with the jet. Studying young jets can reveal information about the composition of the launched material and impact that the shocks can have on the chemical composition of the whole system.

The spin-up of the infalling envelope results in flattening of the material surrounding a star into a disk-shaped structure. In those disks, the first seeds of planets are created as the dust grains collide and coagulate. The dust grains are coated by ices, not only water, which is the main component of the ice. Other molecules such as CO (carbon monoxide) can also freeze-out from the gas-phase onto the grains and be converted to species like CH_3OH (methanol) and H_2CO (formaldehyde). Knowing the composition of those ices means knowing what provides the building blocks of the cores and atmopsheres of planets. Whether the molecule will be present in the gas phase or in the ice, depends on the temperature: water freezes onto the grains below 100 K and CO below 20 K. The temperature of the disk decreases with distance from the protostar, and the layer beyond which a certain molecule is present predominantly in the ice is called the iceline. Icelines play an important role in planet formation as they can facilitate the pile-up of material, but they also effectively change the composition of the building blocks of planets.

Measured dust masses of mature disks show that when envelope has dissipated they do not have enough mass to make the solid cores of planets. Does that mean that planets start to form early? There are several evidences for that: meteorites seen in our Solar System are divided in two classes between inner and outer part as if a massive planet formed and separated them very early on. Also, dust grains have been observed to grow very quickly in disks.

This thesis

This thesis presents observational efforts to characterize the earliest stages of star and planet formation. In Chapter 2 we use VLA observations at 4 and 6.4 cm of 100 protostars in the Perseus molecular cloud to study the ionized jet component and show that the ionized jet properties are connected to the stellar properties. For the observed large sample of sources,

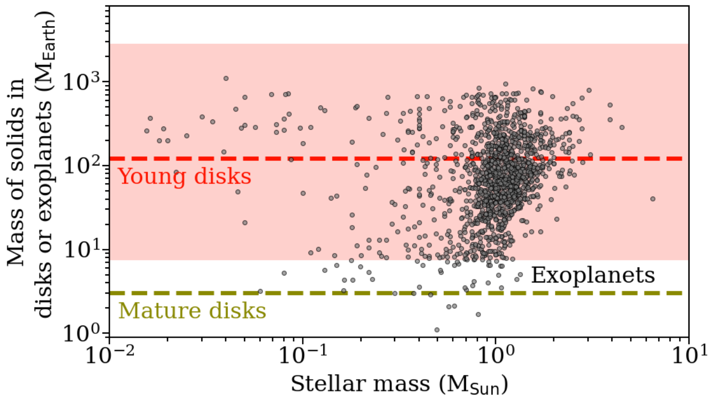

Figure 3: Plot showing the distribution of masses in solids of exoplanetary systems for planets around main sequence stars with the measured stellar masses (taken from exoplanet.eu). The shaded red area marks the range of the best estimate of dust disk masses in the Perseus molecular cloud with median mass indicated with the dashed line. The median dust mass of mature disks is shown in yellow.

we use information on the jet fluxes to correct the measurements of disk masses at shorter wavelengths. This allowed to compare dust masses of young disks with those of older disks for the first time and opened a question: is there enough solid material to make planets in the youngest disks?

We follow up on that question in Chapter 3, in which we combine observations of ALMA and VLA to characterize the dust in young disks. By comparing the dust masses of young disks with exoplanetary systems we show that the solid cores of gas giants can be formed in the earliest stages. This result is highlighted in Figure 3: observed exoplanets have masses in solids that are well above those of the mature disks, but are within the range of the dust masses of young disks.

In Chapter 4 we probe the chemical composition of high-velocity jets towards several protostars in the Serpens molecular cloud. We confirm that the C/O ratio of the jet is lower than that of the surrounding envelope; this shows that studying young jets can potentially be crucial to probe the inner regions of disks.

Chapter 5 provides an overview of the chemical tracers of different physical components of protostellar systems. ALMA observations of a dozen protostars enable to dissect these different components. This can also be used to measure the temperature (e.g., DCO^+ and N_2D^+ are a cold gas tracers) or nature of the energetic radiation (C_2H and CN as products of UV dominated chemistry).

This thesis can be summarized as follows: Planet formation starts early, in the first 0.1 Myr of stellar life in very young disks. Characterization of those young systems is essential for understanding the conditions of planet formation. Interferometric observations of molecules at Solar System scales are incredibly useful to describe those conditions. Molecular jets, which we show to be very common in young systems, can be particularly important to inform about the innermost regions of young disks.

Future outlook

Observers of young protostellar systems are in for an exciting future: ALMA is now at full speed revealing its amazing capabilities, able to resolve young protostars and their disks at Solar System scales. It is especially well suited to provide good characterization of young protostellar jets, which hold the mystery of the chemical composition of the inner regions of disks. A revolution is imminent with the JWST telescope, the largest dish ever launched to space. Especially the MIRI instrument will characterize protostars at similar resolution to ALMA, in the 5-28 micron range unreachable from the ground, and will reveal hot gas as well as ice mantle composition. Combined with ALMA information on the physics and chemistry of colder gas and kinematics of the individual components, we will soon have the clearest view ever on the onset of planet formation.