Probing the inner regions: a multi-wavelength view of accretion and outflow in protoplanetary disks

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ENGLISH SUMMARY

For centuries, humans have gazed at the sky and wondered about the origin of the Earth and the Sun. Countless stars and more than 6000 planets have been discovered beyond our Solar System. Most of these 'new worlds' differ markedly from our own, revealing both the uniqueness of the Solar System and the complex, varied outcomes of planet formation. Characterizing the processes of formation and evolution of planetary systems is therefore essential for understanding our Solar System.

Star formation and protoplanetary disks

Stars form in giant molecular clouds, cold and dense regions in the interstellar medium composed primarily of gas ($\sim 99\%$) and of a small fraction of sub-micron dust grains ($\sim 1\%$; Figure 1; panel (a) and (A)). These clouds contain denser filamentary sub-structures, along which pre-stellar cores reside (Figure 1; panel (b) and (B)). Fed by material accreting from the surrounding cloud, some of these cores become sufficiently dense to undergo gravitational collapse and form a (or multiple) protostar.

The newly formed protostar continues to accrete mass from the surrounding envelope. To conserve angular momentum, some of the accreting material flattens into a circumstellar disk, which simultaneously channels matter onto the star. Over time, this disk becomes more prominent and massive, as angular momentum is redistributed within and removed from the system through viscosity and/or the launch of protostellar outflows and jets (Figure 1; panel (c), (C), (d) and (D)).

As the system evolves and time passes, an increasing fraction of its mass resides in the star and in the disk compared to the remnant envelope. After ~ 1 Myr, the envelope is dispersed, and in $\sim 5 - 10$ Myrs the disk itself is completely dissipated through a combination of accretion onto the star and dispersal processes.

During the lifetime of the disk, dust grains collide and clump together, forming pebbles of bigger and bigger size, and eventually forming planetary embryos and planets (Figure 1; panel (e)). To indicate that it is the birthplace of planets, circumstellar disks are commonly referred to as protoplanetary disks.

Probing the inner regions

High-resolution and high-sensitivity observations of protoplanetary disks conducted with the Atacama Large Millimeter/submillimeter Array (ALMA) in nearby star-forming regions have revealed that nearly all large disks host substructures – present both in gas and dust emission – such as rings and gaps, large cavities, spirals, and crescents.

A distinct subclass of these ringed and gapped disks is transition disks,

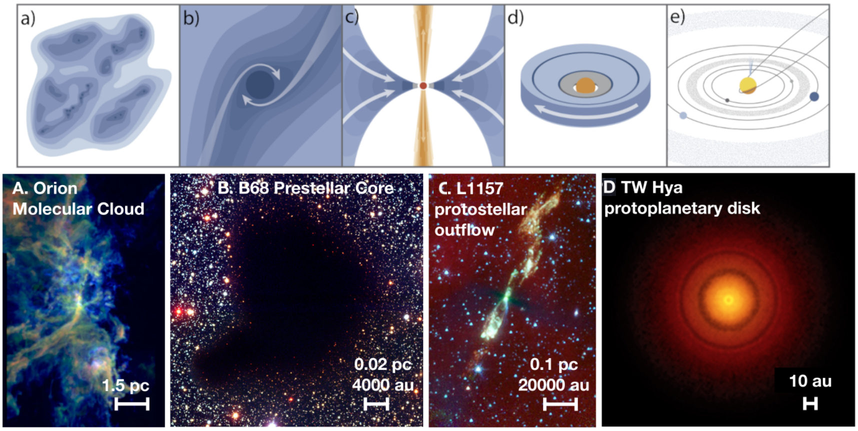

Figure 1: *Top:* Cartoon of the different stages characterizing Solar-like star and planet formation. *Bottom:* A. The Orion Molecular Cloud (OMC) as seen in CO emission; B. the B68 prestellar core; C. The outflow L1157 in infrared emission; D. Protoplanetary disk TW Hya. Adapted from Öberg et al. (2021).

characterized by large inner dust cavities (> 20 au), often interpreted as the result of dynamical clearing by a massive companion, such as giant planets or low-mass brown dwarfs. These cavities are not completely devoid of material, but instead allow gas and dust to flow inward. Both continuum and ^{12}CO gas emission are detected with a centrally peaked morphology close to the central star, consistent with ongoing accretion. However, although the continuum emission close to the star is often attributed to thermal dust from an inner disk, its true origin remains uncertain, as free–free emission from ionized gas is expected to contribute significantly at low frequencies, highlighting the importance of investigating this component in both transition and full disks.

This thesis

This thesis investigates the processes of formation and evolution of protoplanetary disks from an observational point of view, with a particular focus on the accretion and ejection mechanisms. In particular, using archival ALMA and VLA observations, in each chapter, we primarily address these questions:

- What is the origin of the central emission detected within the cavity of transition disks?
- What mechanisms drive accretion onto the protostar in protoplanetary disks?

- How are accretion and outflow processes related in protoplanetary disks exhibiting different types of substructures?

- In what ways do the cavities of transition disks differ in disks around early-type and late-type stars?

Chapters 2 and 3 of this thesis address the first three questions. In Chapter 2, we investigate the origin of the central emission in transition disks, analyzing spatially resolved, multi-wavelength ALMA observations of the millimeter continuum emission, combined with literature centimeter data. In most of the disks, we find that the central emission close to the star is dominated by free-free emission, likely associated with an ionized jet or wind. Using a physical jet model based on protostellar jets, we convert the free-free emission into an ionized mass-loss rate. A strong correlation between the ionized mass loss rate and the accretion rate is found, suggesting that the outflow is strictly connected to the stellar accretion and that accretion in these disks is mainly driven by a jet and/or MHD wind. In Chapter 3, we expand this analysis to a larger sample of full protoplanetary disks (i.e., disks without large inner cavities). Excess free-free emission over the contribution of the thermal dust is also detected in these disks. We find that this excess emission most likely originates from ionized gas associated with a jet or MHD disk wind. Consistently, a similar correlation between the ionized mass-loss rate (inferred from the free-free emission) and the accretion rate is found for both transition and full disks. Moreover, we find that strong accretors ($\dot{M}_{\rm acc} > 10^{-8} M_{\odot}\ \ {\rm yr}^{-1}$) tend to show lower jet efficiency than weaker accretors.

In Chapter 4, we focus on AB Aur, one of the brightest transition disks in terms of compact free-free emission. By collecting all available high-resolution ALMA and VLA observations, we analyze the compact emission within its cavity over a time span of 8 years. We find the emission to be offset in the south-east direction of the star, with ALMA peak positions typically 25 mas ($\sim$ 4 au) offset from the star and VLA emission typically 47 mas ($\sim$ 7 au) away. Remarkably, the ALMA peak positions vary direction across different years, consistent with a counterclockwise precessing jet with a degenerate orbital period of $\sim 2-9.2$ years and an orbital radius of $\sim$ 3 au. This jet precession may result from a precessing inner disk, possibly caused by the dynamical perturbation of a (binary) companion orbiting outside the inner disk.

The last chapter, Chapter 5, of this thesis addresses the last of the research questions reported above, investigating the gas and dust structures in a sample of three transition disks around K and M stars. These three disks present dust cavities of 30–40 au in radius, with no inner dust disk detection. The CO emission extends inside the cavity with progressively smaller CO cavity radii for the more abundant isotopologues. The observed structures could be explained by super-Jovian companion on eccentric orbits, but further modeling is needed to confirm this conclusion. Contrary to expectation, no significant differences in the brightness temperature or in the gas-to-dust ratio are found between our disks and other transition disks around more luminous stars. This suggests that parameters other than luminosity play a role in setting the gas temperature structure, requiring individual-target studies through thermochemical modeling or multi-transition analyses to constrain the properties of the dust and gas cavities.

Future outlook

The work presented in this thesis highlights the importance of characterizing the inner regions of transition disks, as well as the importance of quantifying the contribution of free-free emission from ionized gas close to the star, both in transition and full disks. Multi-wavelength observations are fundamental for disentangling the thermal dust emission from the free–free component. In this perspective, future observational efforts should focus on expanding the sample of both transition and full disks, including observations at centimeter wavelengths with VLA and ALMA Band 1, where the contribution of the free-free emission is expected to dominate. In combination with higher frequency ALMA data, such observations will enable us to quantitatively investigate the free-free emission contribution and strengthen the observed correlation between the accretion rate and the ionized mass loss rate. In particular, since the current sample of transition disks is biased toward high accretors, new observations of highly accreting full disks and weakly accreting transition disks are required to assess possible differences in jet efficiency, and thus in transport of material, between these two classes of disks.

When possible, ALMA and VLA observations should be complemented by JWST and ELT observations to constrain the chemical composition of the inner regions and to relate the properties of the free-free emission to the molecular species detected in the outflows.

Looking further ahead, the next-generation Very Large Array (ngVLA) and the Square Kilometre Array (SKA), and major upgrades to mm/sub-mm interferometers (ALMA WSU and ALMA2040) will play a fundamental role in studying free-free emission in disks. Their unprecedented resolution and sensitivity will allow for spatially resolving the cavities and the inner region of disks down to the au-scales, even at cm wavelengths.

Together, the capabilities of ALMA, the VLA (and in the future, the ngVLA and SKA), JWST, and ELT provide a true multi-wavelength toolkit for imaging and probing the inner regions of protoplanetary disks with high resolution and sensitivity. This comprehensive approach is essential for advancing our understanding of accretion and ejection processes, and ultimately, of the evolution of these systems.