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Early phases of planet formation in young protostars

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Abstract

One of the most impactful images in the field of star and planet formation was provided a decade ago by the Atacama Large Millimeter/Submillimeter Array, revealing a spectacular planet-forming disk surrounding the young star HL Tauri. This image not only demonstrated the power of this new telescope but also changed a scientific paradigm, since planetary genesis was not expected in such young protostars.

After tremendous efforts from the community to characterise protoplanetary disk substructures surrounding young stellar objects and its link with planet formation, there is a consensus on substructures such as gaps, rings, or spirals being ubiquitous and well-developed in disks surrounding Class II protostars. Nevertheless, when these substructures start to develop in disks, whether they are signposts of young planets or if planets are indeed responsible for producing them is still a lively topic of discussion.

This work reviews the efforts that have been made so far to characterise the earliest phases of planet formation in the most embedded disks surrounding young protostars.

1 Introduction

Three decades ago, the Solar System was the only confirmed planetary system, consisting of inner rocky planets close to the central star, the Sun, and outer giant planets surrounded by massive gaseous atmospheres.

Based on the singular planetary system we knew, the Solar Nebula Hypothesis provided a straightforward and plausible framework for explaining the formation and evolution of the Solar System. This model proposed that the Solar System formed simultaneously with the Sun, as a byproduct of the star formation process. It suggested that a rotating interstellar cloud of dust and gas flattened into a disk-like structure, where planets gradually formed orbiting the Sun at the end of the star formation process. The hypothesis was first introduced by Immanuel Kant in Universal Natural History and Theory of the Heavens [Kant(1755)] and later refined by Pierre-Simon Laplace [de Laplace(1796)].

In 1995, Michel Mayor and Didier Queloz discovered 51 Pegasi b, the first exoplanet detected orbiting a Sun-like star [Mayor & Queloz (1995)]. This planet was a hot Jupiter, a giant gas planet orbiting very close to its host star. A decade later, the first direct image of an extrasolar planet was obtained [Chauvin et al.(2004)], capturing a giant cold planet orbiting a brown dwarf. These early discoveries hinted that planets orbiting other stars could be remarkably different from those in our Solar System. Since then, over 6000 exoplanets have been detected, revealing an exotic diversity that includes hot and cold Jupiters, mini-Neptunes, super-Earths, Earth-sized planets, and ocean worlds such as those suspected to exist on some moons around Jupiter and Saturn (Fig. 1).

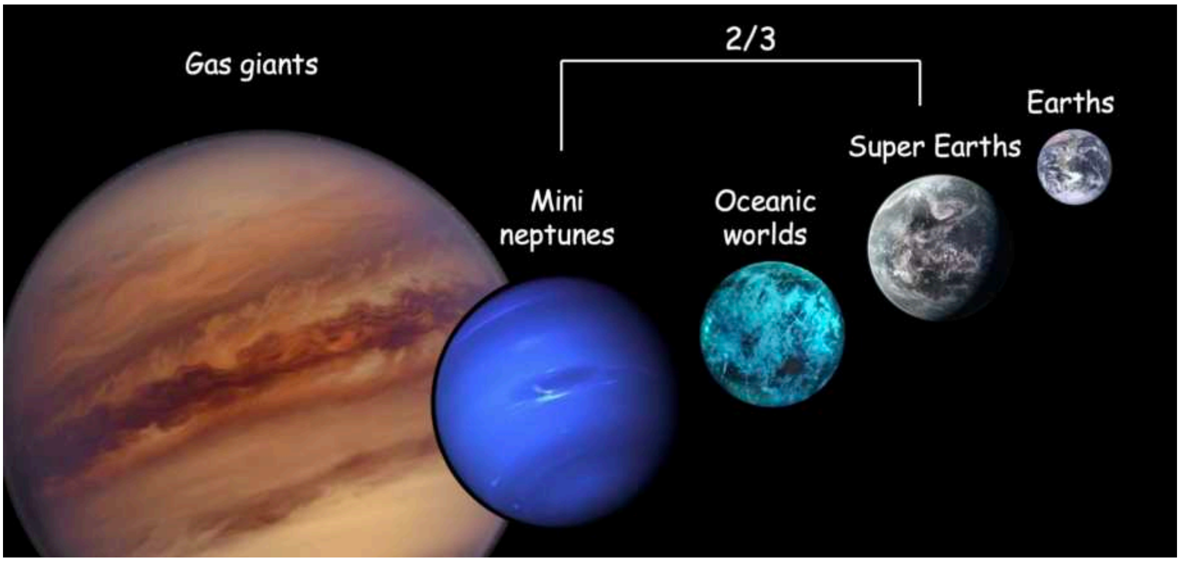

Figure 1: Exoplanet zoo. Super-Earths and mini-Neptunes are the most common types of planets detected in the galaxy

The architectures of exoplanetary systems can also differ from that of the Solar System. One of the best examples is the TRAPPIST-1 system, which comprises seven super-Earths orbiting an ultra-cool dwarf star [Gillon et al.(2017)].

The number and types of known exoplanets are intrinsically biased by the limitations of current detection techniques. Next-generation ground-based and space facilities equipped with advanced instruments will significantly expand this census, enabling the study of Earth-like exoplanets orbiting Sun-like stars, along with their atmospheric compositions. One of the most prominent examples of these next-generation facilities is the Extremely Large Telescope (ELT) of the European Southern Observatory, currently under construction in northern Chile.

Planet formation theories face the challenging task of explaining the diversity of planetary architectures. Currently, there are two primary theories of planet formation: the core accretion model and the disk gravitational instability model. In the core accretion model, small particles coagulate gradually growing into larger bodies that form the rocky cores of planets, sufficiently massive to accrete gas and form planetary atmospheres [Lissauer(1993)]. While this model explains the formation of terrestrial planets, it is too simplistic to explain the formation of gas giants, as the predicted formation timescales exceed the typical lifetimes of gas disks. This limitation is addressed by the disk gravitational instability model, which proposes that massive protoplanetary disks fragment into self-gravitating clumps, allowing for the rapid formation of gas giants [Boss(1997)]. Nevertheless, neither of these theories can explain well the formation of hot Jupiters.

To refine these planet formation theories we need not only more sensitive observations but also access to data from the earliest stages of star and planet formation. At these stages, protostars are surrounded by a cold, dense envelope and a flattened structure of cold dust and gas, where planets will eventually form. Telescopes like the Atacama Large Millimeter/submillimeter Array (ALMA) are crucial for understanding when and how this process begins.

2 Early phases of planet formation

The advent of the Atacama Large Millimeter/Submillimeter Array, with its superb sensitivity and angular resolution, has revolutionized the field of star and planet formation. The first image of a dust disk surrounding the young Class I-II source HL Tauri (Fig. 2), taken as part of the science verification phase of ALMA's longest baseline capabilities, transformed our understanding of planet formation theories. This single image modified an entire paradigm, as the wealth of rings and gaps observed indicated that planet formation had already begun in the earliest stages of the formation of a star [ALMA Partnership et al.(2015)].

Since that image, and thanks to follow-up studies that aimed to characterize the structures of protoplanetary disks in a large dataset of young stellar objects, mainly Class II protostars, we now know that planet formation begins earlier than previously thought, as demonstrated in the case of HL Tau. Furthermore, planets form within protoplanetary disks, as shown in images of protoplanets in the source PDS 70 [Müller et al.(2018), Benisty et al.(2021)]. Substructures such as rings, gaps, spiral arms, and dust traps are intimately related to the presence of planets; however, it is not entirely clear what came first. Some of these structures could be shaped by planets, while density enhancements could contribute to the formation of planetesimals. Thanks to ALMA Large Programs like the "Disk Substructures at High Angular Resolution Project" (DSHARP) [Andrews et al.(2018)], we also know that substructures are ubiquitous in Class II protostars.

Nevertheless, many questions remain unanswered, and when and how planet formation starts is still unknown.

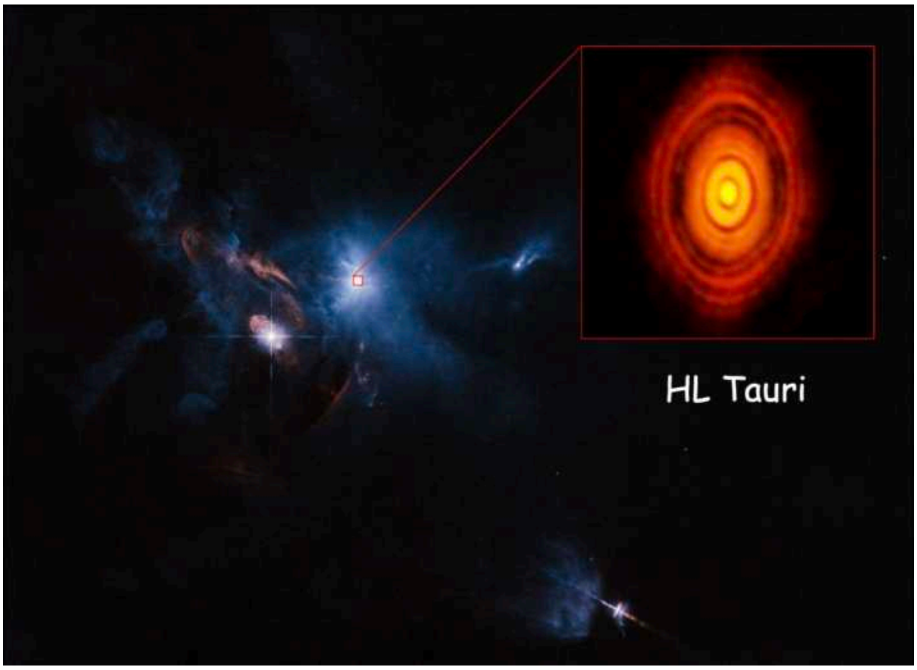

Figure 2: ALMA/Hubble composite image of the region around HL Tauri (Credit: ESO). The ALMA continuum data at 1.3 mm is enlarged in the upper right box, tracing a dust disk surrounding the young protostar HL Tauri.

3 Substructures in embedded disks around Class 0-I protostars

Nowadays, the community studying star and planet formation is focusing its efforts on understanding when planet formation begins. Observational studies have indicated a lack of mass in protoplanetary disks surrounding Class II sources to form planets [Manara et al.(2018)]. With the caveat of uncertainties in the measurement of disk dust masses, which may be underestimated, these results suggest either an early formation of planet cores during the embedded phase, when protoplanetary disks are more massive, or that disks are continuously replenished by fresh material from the environment, providing enough material to form planets.

ALMA, with its longest baseline capabilities, offers for the first time the possibility to study disk substructures in embedded protostars with sufficient spatial resolution and sensitivity. This is exemplified by GY 91 [Sheehan & Eisner(2018)] and IRS 63 [Segura-Cox et al.(2020)], which show annular dust substructures in disks around embedded Class I protostars, confirming hints of planet formation in embedded phases and concluding that younger disks play an important role in the onset of planet formation.

3.1 Early planet formation in embedded disks: the eDISK ALMA Large Programme

The ALMA Large Programme "Early planet formation in embedded disks" (eDISK; Fig 3) was designed to test the ubiquity of rings and gaps in protoplanetary disks surrounding young protostars, aiming to investigate planet formation at the earliest phases of the formation of stars [Ohashi et al.(2023)].

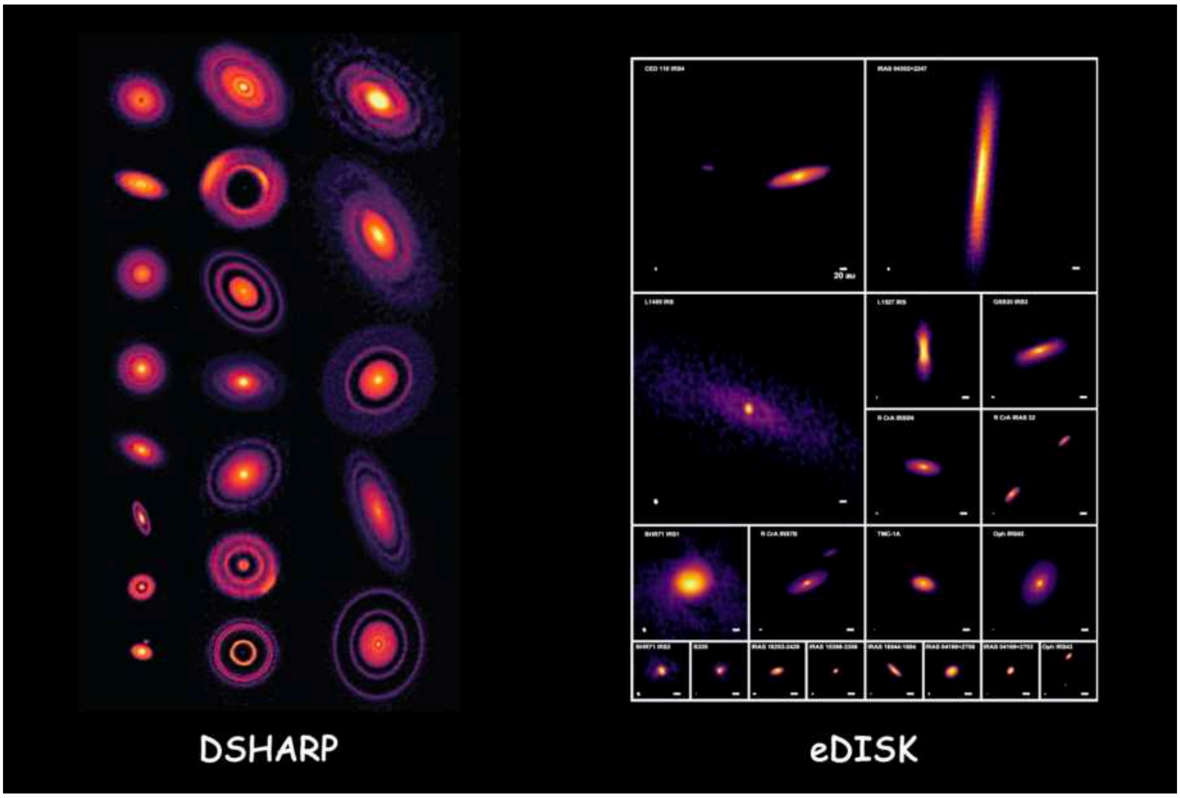

Figure 3: Dust continuum emission at 1.3 mm, observed with ALMA. Comparison between DSHARP Class II disks (left) and eDISK Class 0-I disks (right).

This program observed 12 Class 0 and 7 Class I sources in nearby star-forming regions ($<$200 pc) at 1.3 mm and at a spatial resolution of 0.04" ($\sim$7 AU). The aim was to detect dust disk substructures and to identify kinematically embedded disks rotationally supported, distinguishing them from their surrounding envelopes. Another goal was to identify chemical tracers of the disks.

The **dust continuum emission** images at 1.3 mm reveal elongated structures of different sizes, suggesting that the dust traces disks. The dust disks exhibit smooth emission with no obvious sharp ring-like or spiral-like structures, unlike those observed in more evolved Class II sources. Brightness asymmetry is observed in several sources, primarily along the minor axis. Three of the most evolved sources (Class I) display faint ring-like structures.

One of the main conclusions of this work is that sharp substructures do not seem to be well developed in the embedded phase, suggesting rapid formation as Class 0/I protostars evolve into Class II. On the other hand, the high optical depth of dust emission at 1.3 mm may obscure these substructures, and the compact, highly inclined disk-like structures observed in several sources could hinder the detection of substructures at a resolution of 7 AU. Longer wavelengths observations tracing optically thinner dust will be needed to better assess the presence of dust disk substructures.

The brightness asymmetry primarily observed along the minor axis could be attributed to a geometrical effect in which the far side of a highly inclined disk with finite vertical thickness appears brighter than the near side. This suggests that the dust has not yet completely settled onto the disk midplane during the embedded phases, but it settles rapidly as embedded disks evolve into Class II disks.

The **gas emission** played a major role in this project to disentangle emission associated with embedded Keplerian rotating disks from material coming from the surrounding envelope. Most of the sources in the sample exhibit the presence of a Keplerian disk, primarily observed in $C^{18}O$ and ^{13}CO, which allows an estimation of the dynamical mass of the central protostar.

Moreover, gas emission traced by different molecular species included in the ALMA observations setup reveals a myriad of protostellar features that vary from source to source, including outflows, emission from envelope material, and streamer-like features.

In the case of outflows, several sources exhibit different components. One of the best examples is the Class 0 source GSS30 IRS3 [Santamaría-Miranda et al.(2024)], where ^{12}CO emission reveals the coexistence of a jet and a disk wind. Other sources display outflow shell-like structures that suggest episodic ejection events, as seen in the Class I source Oph IRS 63 [Flores et al.(2023)]

One of the most unexpected results of this study is the clear presence of streamers of material connecting the envelope with the disk in some of the sources of the sample. In the case of Oph IRS 63, streamers are detected at larger scales through $C^{18}O$ emission and on smaller scales via SO, showing an infalling and rotating structure that continuously feeds the disk. By comparing the envelope-to-disk mass infall rate with the disk-to-star mass accretion rate, the authors conclude that the protostellar disk is in a mass build-up phase that could soon become too massive to be gravitationally stable [Flores et al.(2023)].

In the case of the Class 0 source IRAS 16544-1604, large-scale streamers are detected in

^{12}CO, coexisting with smaller-scale streamers traced by SO. This source exhibits an asymmetric dust disk along both the major and minor axes, suggesting the presence of dust spiral features that could be induced by gravitational instability in the disk or by interaction with the observed accretion streamers. Longer wavelengths observations are needed to better infer the disk mass to investigate its gravitational stability [Kido et al.(2023)].

4 Accretion streamers and planet formation

Accretion streamers are narrow flows of material that are coherent in velocity, funneling gas and dust from the outer regions into protoplanetary disks. They represent an evolution in the traditional low-mass star-forming scenario, where a spherical dense molecular cloud collapses homogeneously to produce a protostar with its associated planetary system [Shu(1977)]. Streamers have been detected at various scales, ranging from thousands of AU to a few hundred AU, and have been observed in evolutionary stages from Class 0 to Class II [Pineda et al.(2020), Yen et al.(2019), Gupta et al.(2023)].

Recent results, still limited by current observational capabilities, point to the common existence of streamers with approximately 60% of embedded Class 0 and I protostars associated with them [Valdivia-Mena et al.(2024)].

The community studying star and planet formation is increasingly focusing their attention on these structures, as asymmetric infall has the potential to trigger the formation of disk substructures [Kuznetsova et al.(2022)] and gravitational instabilities that can initiate planet formation in embedded protostellar phases [Kratter et al.(2010)]. This aligns with the latest results pointing to an early formation of planets in young protostars.

Many questions remain open in this field. There is still a lot of work to do to determine which molecular species are the best tracers of streamers, whether the reservoir of material is coming from the envelope or from outside the natal core, and how they modify the chemical properties of the disk, as they deliver fresh material and interact with the disk through shocks. We also need to better understand how efficiently they can trigger disk substructures and disk instabilities, and whether this process involves continuous replenishment of material or episodic phenomena. Indeed, episodic accretion is another discussion topic, as it can change the distance of snowlines outward, impacting the planet formation process. Moreover, one of the possible origins of episodic accretion is related to disk instabilities. Evidence of a connection between accretion streamers and episodic accretion onto central protostars has begun to be reported in very recent publications [Hales et al.(2024)], which needs further investigation with future observations and a larger sample of protostars.

Next generation of interferometers operating between centimeter and submillimeter wavelengths, such as ngVLA, SKA, and the upgraded ALMA, will be crucial for further characterizing accretion streamers and the origin of planets.

5 Conclusions

- When and how planet formation begins remains an open question that requires a holistic study of both dust and gas in embedded protostars.
- Sharp substructures are not well developed in the embedded phase, suggesting a rapid formation between Class I and Class II stages. This needs confirmation at longer wavelengths where the dust is optically thinner.
- Accretion streamers connecting the envelope to the disk may play a significant role in replenishing material in disks. They are potential triggers of planet formation at the earliest stages, and their connection with episodic accretion onto protostars needs to be understood.
- There is a promising future for studying key questions on the earliest phases of planet formation thanks to the next generation of interferometers such as ngVLA, SKA, and ALMA with its wideband sensitivity upgrade.

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