



Substructures in Planet-Forming Disks with the SKAO

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Disks of gas and dust orbiting young stars are the arenas and material reservoirs for planet formation. Over the past decade, multiwavelength observations, from infrared to radio, have resolved the spatial distribution of hundreds of protoplanetary disks in nearby star-forming regions, revealing a diverse zoo of substructures. These substructures are morphological features such as rings, gaps, spirals, vortices, asymmetries, warps, or clumps that trace variations in density, temperature, or composition relative to an otherwise smooth distribution of gas and dust. Many unknowns persist as to the origin of these substructures, their role in planet assembly, and their true properties. SKA-Mid Band 5b continuum observations, offering angular resolutions of $\sim 0.05''$ ($\sim 0.15''$) with AA4 (AA*) at 12.5 GHz / 2.4 cm, will enable new progress at this frontier. In this chapter, we outline the open questions in the field of disk substructure that SKA-Mid is uniquely poised to address, with a lens on dust thermal emission.

1 Introduction

Until a few decades ago, the idea of detecting planets beyond our own Solar System seemed nearly unthinkable. Today, thanks to remarkable advances in instrumentation and analysis techniques, thousands of exoplanets have been discovered, unveiling a striking diversity of planetary systems across the Galaxy. As a result, understanding the origins of these worlds has become a central objective of contemporary astrophysics.

The formation of planets is a complex, multi-stage evolutionary process. Stars are born in clustered regions within massive, dense regions of molecular hydrogen known as giant molecular clouds (Lada and Lada, 2003). The combination of gravity and large-scale turbulent motion in these clouds leads to localized collapses under self-gravity (Larson, 1981; Mac Low and Klessen, 2004). As material condenses, the clouds fragment into smaller and denser regions (Hoyle, 1953). Protostars grow as material from the surrounding cloud or ‘envelope’ accretes through an infalling flow. The initially high stellar multiplicity fraction drops with time as unstable multiples decay into stable hierarchical systems (e.g. Bate et al., 2003).

During the formation of protostars, not all of the surrounding envelope material accretes directly onto the central object(s). Due to angular momentum conservation (Pringle, 1981), a portion of the infalling gas and dust settles into a flattened, rotating structure surrounding the young star, the so-called protoplanetary disk (PPD), which is the cradle of planets. The disk may form once, or even be destroyed and re-form multiple times due to ongoing infall events, ram pressure stripping, and tidal interaction with other protostars (e.g. Bate, 2018).

In this chapter, we primarily focus on disks around Class II sources, which correspond to the evolutionary stage where the protostellar envelope has mostly dissipated and the disk is visible in the infrared. Most substructure observations to date have been conducted in this stage. These disks not only regulate the subsequent accretion onto the star but also play a pivotal role in the redistribution of mass and angular momentum within the system (e.g., Armitage, 2010). Composed primarily of cold gas and fine dust grains, Class II disks typically span from tens to several hundreds of astronomical units in radius. They are now widely recognised as the birthplaces of planets (e.g., see review by Manara et al., 2023). Within these disks, dust grains undergo collisional growth and aggregate into pebbles, which under favourable conditions can eventually form planetesimals and even fully formed planets (reviewed in Drażkowska et al., 2023; Birnstiel, 2024). Therefore, understanding the formation and evolution of PPDs is key to uncovering the common origin of stars and planets (McCrea, 1960).

Although PPDs were first predicted through theoretical studies (Lynden-Bell and Pringle, 1974; Cassen and Moosman, 1981; Ruden and Lin, 1986; Kenyon and Hartmann, 1987), their properties have only been confirmed and explored in detail through observations. As an observation-driven field today, the most effective way to study PPDs is through direct imaging with telescopes. Fortunately, the rapid development of astronomical facilities over the past decade, particularly the emergence of powerful radio interferometers such as the Atacama Large Millimeter/submillimeter Array (ALMA) and the Karl G. Jansky Very Large Array (VLA), has allowed us to resolve these disks with unprecedented clarity. Arguably, the most transformative discovery in this field over the

past decade, dating back to the unveiling of the HL Tau image in 2014 — the same year as the last Square Kilometre Array (SKA) science book (Braun et al., 2015; Hoare et al., 2015) — is the detection of substructures in PPDs (ALMA Partnership et al., 2015).

Direct imaging observations have revealed that PPDs exhibit remarkable diversity in their structures (see review by Bae et al., 2023), chemical compositions (reviewed in Öberg et al., 2023), and evolutionary stages (see review by Williams and Cieza, 2011). In this chapter, we focus on how the upcoming SKA can be utilised to observe substructures within PPDs, highlighting the unique advantages, capabilities, and indispensable role of SKA in this context. Other key aspects closely related to planet formation will be addressed in different chapters of this updated edition of the SKA Science Book. Large surveys of PPDs, and the emerging prospects for studying their properties in a statistical framework with the Square Kilometre Array Observatory (SKAO), will be discussed in detail in the "Demographics of planet-forming disks with the SKAO" chapter (Garufi et al., 2026). Complementarily, the opportunities and challenges of observing disks at centimeter (cm) wavelengths, where free-free emission tends to dominate in the innermost regions, are addressed in the "Ionized gas emission in protoplanetary disks with the SKAO" chapter (Guidi et al., 2026), with a focus on the caveats and diagnostic potential of long-wavelength observations. In addition, for the rapidly growing field of chemistry in PPDs, "Unveiling complex chemistry in planet-forming disks with the SKAO" chapter (Podio et al., 2026) demonstrated how observations of emission lines from heavier molecules by SKA, including carbon chains and rings, as well as prebiotic molecules whose peak emission falls in the centimeter regime, can open up new avenues of research.

2 What Are Substructures?

Planet formation and its intricate relationship with PPDs have remained at the forefront of astrophysical research for decades. More precisely, what do substructures represent in the context of observations of disks? Substructures refer to morphological features discernible in resolved images of disks. These can currently be obtained in two main wavelengths regimes, in the millimeter (mm) and submillimeter (sub-mm) range, using facilities such as ALMA, NOEMA, and VLA (e.g., Andrews, 2020), and at optical to infrared wavelengths with space- and ground-based telescopes (e.g., Benisty et al., 2023), including the Hubble Space Telescope (HST), James Webb Space Telescope (JWST), Very Large Telescope (VLT), Gemini (North and South), and Subaru Telescope. As illustrated in Fig. 1, these substructures include spiral arms, cavities, warps, crescents, and other azimuthal asymmetries, but most commonly, rings and gaps.

The term *substructure* emerged to describe localized features *within* the broader structure of a protoplanetary disk. Before the advent of high-resolution facilities disks were generally modeled as smooth, axisymmetric structures. Although some disks were already known to deviate from this simple picture; most notably the so-called transitional disks (e.g., Espaillat et al., 2014), characterized by large inner cavities, and the lopsided or horseshoe-shaped disks revealed in ALMA Early Science results (e.g., van der Marel et al., 2013; Casassus et al., 2013), these were still regarded as single, global structures rather than systems containing smaller-scale features. As higher-resolution imaging became available, observations began to reveal intricate fine patterns embedded within disks. The prefix “sub” thus highlights the emergence of these finer-scale,

internal features within the overall disk structure.

It should be pointed out currently that most substructure studies have focused on Class II disks. Class 0 and Class I protostars represent the embedded phases of star formation, during which the central object is still deeply enshrouded in a collapsing envelope and the surrounding disk is often obscured at optical, near-infrared and even potentially millimetre wavelengths. However, recent high-resolution observations have begun to reveal disk substructures at earlier evolutionary stages (Sheehan and Eisner, 2018; Segura-Cox et al., 2020; Maureira et al., 2024, 2025). In particular, surveys targeting these early-stage systems such as the ALMA large program Early Planet Formation in Embedded Disks (eDisk), have identified a few disks that already show ring-like features, spiral arms, or non-axisymmetric dust distributions (Ohashi et al., 2023). Unfortunately, such detections remain relatively rare, and many early disks appear compact or only marginally resolved even with ALMA's longest baselines (Ohashi et al., 2023).

However, these results may reflect not the absence of substructures but the effect of high optical depths at (sub-)millimetre wavelengths that can obscure underlying features, as suggested by systems exhibiting only low-contrast substructures, e.g., IRS 63 (Segura-Cox et al., 2020). Observations at longer wavelengths, where the dust emission becomes more optically thin, therefore provide a promising avenue to uncover such hidden structures. In this respect, the SKA will play a key role by enabling sensitive, high-resolution imaging of embedded disks in a regime less affected by optical depth effects. These findings suggest that substructure formation may either require time to develop or become more detectable as envelopes dissipate and the disk evolves into the Class II phase (e.g. Hsieh et al., 2025; Maureira et al., 2026).

2.1 Theoretical Framework

Here, we consider a range of mechanisms that can generate substructures in protoplanetary disks. Changes in dust properties near snowlines (Zhang et al., 2015; Okuzumi et al., 2016), intrinsic magnetohydrodynamic (MHD) instabilities (Bai and Stone, 2014; Flock et al., 2015; Wu et al., 2023; Wu, 2024; Su and Bai, 2024), and gravitational instability (Dong et al., 2016; Speedie et al., 2024) have been proposed as possible origins. By contrast, in many cases, substructures are thought to result from the interaction between embedded companions and their disks.

Planets can carve dust-only or dust and gas gaps inside their parental disks (Dipierro et al., 2016), with properties such as gap depth, gap separation, ring width, and ring thickness dependent on the mass ratio between the planet and the star (Dong and Fung, 2017; Dipierro and Laibe, 2017; Kanagawa et al., 2018; Dong et al., 2018; Bi et al., 2021, 2023), as well as excite spirals and asymmetries (Fung and Dong, 2015; Zhu et al., 2015; Dong et al., 2015a). Also, the presence of companion stars can induce prominent features such as spirals and asymmetries (e.g., see reviews by Zagaria et al., 2023; Cuello et al., 2025), and close massive companions can lead to efficient truncation of the disk, producing large inner cavities or compact disks (Artymowicz and Lubow, 1994; Zurlo et al., 2023). These effects are best characterized by the mass ratio between the central star and its companion, which offers a dynamically meaningful criterion in distinguishing between stellar and planetary perturbers (e.g., D'Orazio et al., 2016).

All these mechanisms are not mutually exclusive and may operate simultaneously in different

regions of the same disk. Among the various mechanisms proposed, planet–disk interactions are particularly compelling due to their ability to produce sharply defined substructures (Kley and Nelson, 2012) capable of slowing down dust radial drift. A massive planet embedded in the disk can gravitationally perturb the surrounding gas, carving a gap along its orbit (Lin and Papaloizou, 1980; Paardekooper et al., 2023). In the dust component, this results in the accumulation of grains on either side of the gap, forming prominent ring-like features (Ayliffe et al., 2012; Pinilla et al., 2012a).

These features are often interpreted as dust traps. In such regions, grains are concentrated at pressure maxima in a size-dependent manner. Larger particles tend to be trapped more efficiently than smaller ones (e.g., Drążkowska et al., 2023; Birnstiel, 2024, also see the Disk Demographics chapter by Guidi et al. (2026)), leading to narrower and more sharply defined rings when observed at longer wavelengths (Speedie et al., 2022; Shi et al., 2024; Yang et al., 2025). This behavior is a distinctive prediction of dust trapping and is not expected from alternative processes such as snowline-induced opacity variations. Multi-wavelength continuum observations provide strong support for this interpretation. In several systems, longer-wavelength data consistently reveal more compact ring structures that trace larger grains (Carrasco-González et al., 2019; Macías et al., 2019; Guidi et al., 2022; Doi and Kataoka, 2023; Liu et al., 2024; Sierra et al., 2024).

In recent years, observational evidence supporting the planet–disk interaction hypothesis has grown significantly. Direct detections of forming planets have been reported inside disk cavities, most notably in the cavity of the PDS 70 disk (Keppler et al., 2018; Close et al., 2025a) and within the gap of the WISPIT 2 disk (Close et al., 2025b; van Capelleveen et al., 2025), and candidates of spiral arm driving planets have also been found (e.g., Wagner et al., 2023). Indirect evidence has also emerged from deviations in molecular gas kinematics from Keplerian rotation (Perez et al., 2015; Pinte et al., 2018; Pérez et al., 2018; Casassus and Pérez, 2019; Pinte et al., 2019, 2020, 2025), which have been interpreted as signatures of gravitational perturbations by unseen planetary companions (e.g., Pinte et al., 2023), as well as spiral pattern speed measurements indicating companion origin (e.g., Ren et al., 2018). However, so far there have only been a small number of systems in which complementary spiral features have been found in mm continuum images, despite expectations that they should be detectable (e.g., Speedie et al., 2022; Speedie and Dong, 2022). A plausible explanation is that high optical depths at mm wavelengths may hide the signal. Some examples supporting this idea are Elias 24 (Carvalho et al., 2024) and PDS 66 (Ribas et al., 2025), which show significantly more structure at 3mm than 1.3 mm.

2.2 Observational Framework

Here we briefly introduce the observational framework to contextualize the signatures detected in disk images, followed by a discussion of how radio interferometry at longer wavelengths can uniquely constrain the nature, origin, and evolution of disk substructures. For a more comprehensive treatment of this topic, the reader is referred to the observational primer by Andrews (2020).

Resolving nearby protoplanetary disks in star-forming regions requires remarkably high sensitivity at sub-arcsecond angular resolution. To detect and characterize the finer substructures within these disks, angular resolutions on the order of tens of milliarcseconds (roughly 1-5 AU at 100 pc) are

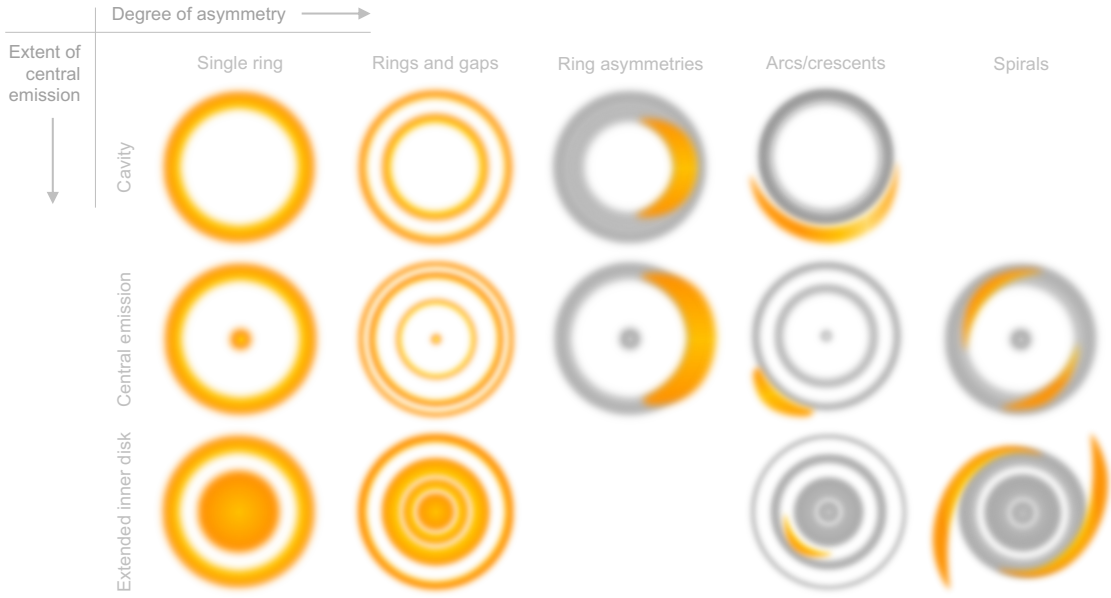


Figure 1: Schematic illustrations of the dust substructures observed in protoplanetary disks in mm continuum emission. The substructures are qualitatively organized in order of increasing asymmetry (to the right), and increasing extent of central emission (going downward). Within each disk illustration, yellow colour highlights the substructure that is labelled at the top of each column. Each illustration is based on a real disk, and blanks in the grid indicate no known examples. First row, left to right: J1604 (231 GHz, [Stadler et al., 2023](#)); LkCa 15, HD 34282, and HD 135344B (332 GHz, [Curone et al., 2025](#)). Second row: DM Tau (230 GHz, [Hashimoto et al., 2021](#)); HD 169142 (232 GHz, [Pérez et al., 2019](#)); AB Aur (230 GHz, [Tang et al., 2017](#)); HD 143006 (240 GHz, [Andrews et al., 2018](#)); HD100453 (343 GHz, [Rosotti et al., 2020](#)). Third row: GW Lup (240 GHz, [Andrews et al., 2018](#)); HL Tau (300 GHz, [ALMA Partnership et al., 2015](#)); blank; HD 163296 (240 GHz, [Andrews et al., 2018](#)); Elias 27 (240 GHz, [Huang et al., 2018](#)).

necessary. Such resolution can be achieved with 8-meter class telescopes operating in the optical and infrared, and with interferometers in the radio.

In terms of sensitivity, however, the challenge becomes more nuanced. Arguably, the most successful instruments in probing disk substructures to date have been ALMA and VLT/SPHERE, both of which have systematically delivered the sharpest and most detailed views.

The current observational landscape reveals that different regions of PPDs are best probed at different wavelengths and through distinct tracers. Scattered and polarized light in the near-infrared is particularly sensitive to small dust grains in the disk surface layers (VLT), while thermal continuum emission in the sub-mm (ALMA) and mm (VLA) regimes trace dust grains closer to the midplane. This has been a theoretical prediction for a very long time ([Weidenschilling, 1977](#)) but is now confirmed with observations. This is easiest to do with edge-on disks (e.g., [Villenave et al., 2020, 2022](#); [Tazaki et al., 2025](#)), also many other works are starting to constrain settling at mm wavelengths on moderately inclined disks ([Pinte et al., 2016](#); [Doi and Kataoka, 2021](#); [Pizzati et al., 2023](#)).

The most abundant molecule after H_2 is CO, and most of the advancements in characterizing

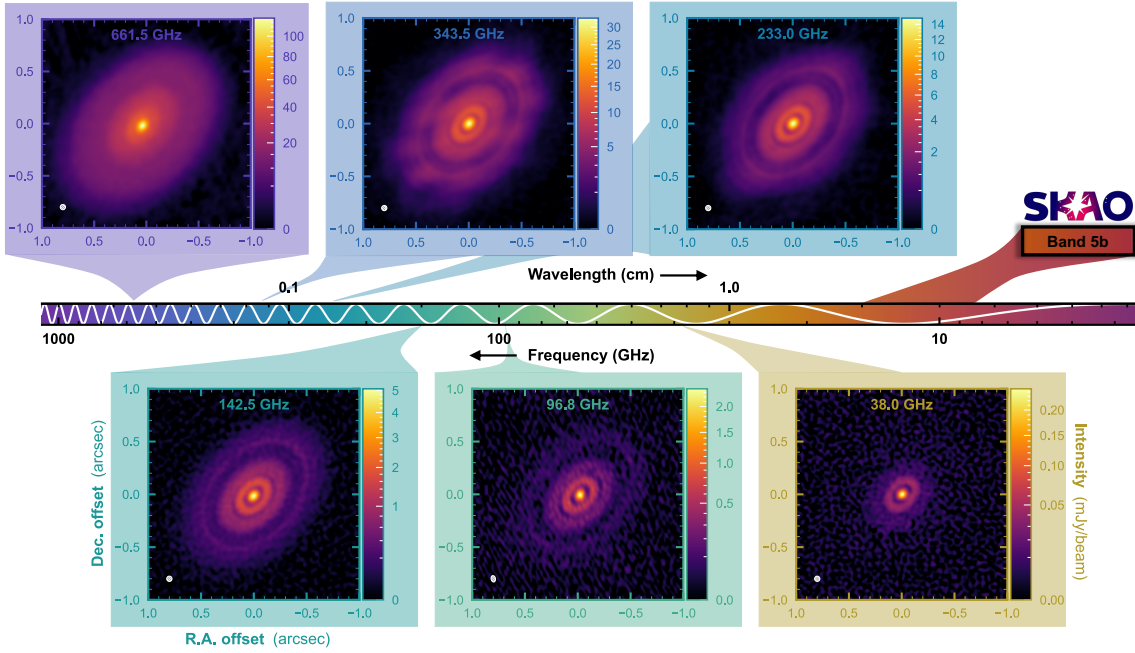


Figure 2: An overview of continuum observations, obtained in the last decade, spatially resolving the distribution of dust in the disk around HL Tau at (sub-)mm wavelengths. SKA-Mid will extend our view to sub-cm wavelengths that are presently unexplored, providing sensitivity to larger grains and optically thinner emission. This chapter focuses on continuum observations with Band 5b (8.3 – 15.4 GHz observing frequency range with 2×2.5 GHz available bandwidth). See Figures 4 & 5 for our predicted SKA-Mid views of HL Tau. First row: ALMA Band 9 (0.45 mm, Guerra-Alvarado et al., 2024); Band 7 (0.87 mm, ALMA Partnership et al., 2015); Band 6 (1.3 mm, ALMA Partnership et al., 2015). Second row: ALMA Band 4 (2.1 mm, Ueda et al., 2025); Band 3 (3.1 mm, Ueda et al., 2025); VLA Ka+Q (7.9 mm, Carrasco-González et al., 2016, 2019).

substructures in the gas phase have been achieved through spectral line observations of CO isotopologues, particularly tracing the upper layers of the disk. Here, kinematic studies have been provided extremely helpful at recovering the velocity gradients revealing the underlying physics in planet-forming disks.

2.3 Advances in Disk Observations

Prior to the publication of *Science with the SKA* book (Braun et al., 2015), sub-arcsecond observations had already uncovered key signatures of large-scale structures in protoplanetary disks, particularly around Herbig Ae/Be stars. Among the most striking early results were the discoveries of prominent crescent-shaped dust concentrations near the edges of wide cavities in Oph IRS 48 (van der Marel et al., 2013) and HD 142527 (Casassus et al., 2013). These features, often referred to as dust traps, were interpreted as the result of gas pressure maxima concentrating mm-sized grains, offering some of the earliest indirect evidence of disk-planet or circumbinary interactions. Concurrently, the characterization of large inner cavities—typical of so-called transitional disks—was recognized as a hallmark of a critical evolutionary phase, potentially linked to planet formation. Additionally, gas observations of HD 142527 revealed non-Keplerian kinematics (Rosenfeld et al.,

2014; Casassus et al., 2015), and when compared with shadows seen in scattered light imaging from the VLT, provided striking evidence that protoplanetary disks need not be confined to a single plane (Marino et al., 2015). Instead, strong misalignments between inner and outer disk regions are not only permitted by the physics, but are now known to be common in nature (Ansdell et al., 2020; Bohn et al., 2022; Villenave et al., 2024). While these early findings laid the foundation for subsequent surveys and modeling efforts, the precise origin and long-term stability of such asymmetric structures remain topics of active investigation (van der Marel et al., 2021).

Then came the HL Tau image in November 2014, a flagship result that demonstrated the transformative potential of ALMA’s long-baseline capabilities. The image astonished the community and catalyzed a revolution in the theory and modeling of protoplanetary disks. Achieving a spatial resolution of approximately 4 au, the HL Tau disk revealed up to seven bright rings and seven dark gaps (the right one of first row in Fig. 2, ALMA Partnership et al., 2015), tantalizing evidence that planet formation may already be underway in a disk less than a million years old (Dong et al., 2015b; Dipierro et al., 2015; Jin et al., 2016).

Out of a sample of just over 100 PPDs observed at sufficiently high angular resolution, which typically means angular resolutions better than 0.05 to 0.1 arcseconds at sub-mm wavelengths, more than 50% exhibit clear substructures such as rings, gaps, or asymmetries (Long et al., 2018; van der Marel et al., 2019). The remainder typically appears compact or featureless at current resolution limits. However, as observational capabilities continue to improve, particularly in terms of spatial resolution and sensitivity, some of the previously unresolved disks increasingly reveal substructures as well. Others, especially the compact disks, may remain smooth at mm wavelengths due to high optical depths (Chung et al., 2024). Observations at cm-wavelengths, where the optical depths are much lower, are essential to understanding the nature of the discs that appear smooth.

Although a wealth of observational evidence supports the idea that planets induce substructures in PPDs, a significant challenge remains in bridging the gap between mm-sized dust grains and kilometer (km)-scale planetesimals. Collisions between mm-sized particles frequently lead to fragmentation or bouncing, rather than the cohesive growth needed for planetesimal formation (see review by Blum and Wurm, 2008). Moreover, solid particles in the disk experience aerodynamic drag from the surrounding gas, which drains their angular momentum and drives them inward toward the central star on rapid timescales (Weidenschilling, 1977). While mechanisms such as the streaming instability (e.g., Youdin and Goodman, 2005; Johansen et al., 2007; Li et al., 2019; Wu et al., 2024a) and pebble accretion (e.g., Ormel and Klahr, 2010; Lambrechts and Johansen, 2012; Johansen and Lambrechts, 2017) have been proposed to accelerate this growth process, the transition from mm-sized grains to cm-sized pebbles remains poorly understood and is critical to advancing our understanding of planet formation.

At mm wavelengths, dust opacity is primarily governed by mm-sized particles (Draine and Lee, 1984; Semenov et al., 2003; Draine, 2006), making ALMA, which operates in the 0.3–3 mm range, highly effective at tracing this dust population. However, ALMA’s sensitivity significantly diminishes for larger, cm-sized grains, limiting its ability to probe this crucial size regime. Figure 3 presents a theoretical estimate of the maximum dust size attainable in protoplanetary disks. The dust size in the disk is thought to be regulated either by radial drift (a_{drift}) or by collisional

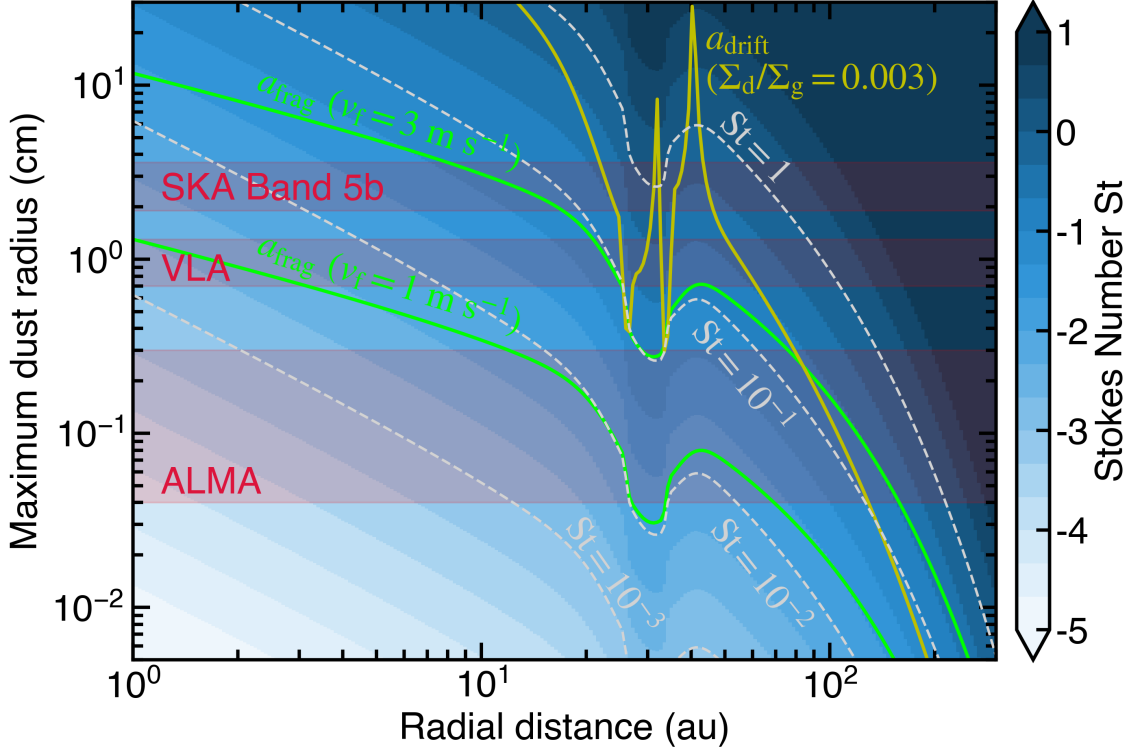


Figure 3: Maximum dust sizes regulated by radial drift (yellow solid line) and collisional fragmentation (green solid lines) in protoplanetary disks (Birnstiel, 2024), overlaid with the typical dust sizes probed by ALMA, VLA, and SKA. The maximum sizes for drift and fragmentation are computed assuming a turbulence strength of $\alpha = 3 \times 10^{-4}$ and a gas surface density profile of $\Sigma_g = 1000 (r/\text{au})^{-1} \exp(-r/50 \text{ au}) \text{ g cm}^{-2}$ with including a gap structure expected for a Neptune-mass planet at 30 AU (Kanagawa et al., 2017).

fragmentation (a_{frag}). The maximum size determined by fragmentation strongly depends on the critical fragmentation velocity (v_f ; typically expected to be on the order of 1–10 m s^{-1}), above which colliding dust aggregates break into smaller pieces. Dust grains can grow beyond the millimeter regime probed by ALMA, and this observational challenge becomes more significant toward the inner regions of the disk. The SKA will be able to directly trace cm-sized dust grains, providing a powerful observational handle on the largest solids and substantially alleviating the current limitations in testing dust evolution models.

Recent ALMA large programs, such as The Disk Substructures at High Angular Resolution Project (DSHARP; Andrews et al., 2018), Molecules with ALMA at Planet-forming Scales (MAPS; Öberg et al., 2021), exoALMA (Teague et al., 2025), and The ALMA Survey of Gas Evolution of PROtoplanetary Disks (AGE-PRO; Zhang et al., 2025), have revealed that gas disks with CO emissions and dust disks traced at sub-mm/mm wavelengths can differ substantially in both spatial extent and morphological features. CO observations from the MAPS program, for example, show that gas disks often extend well beyond the continuum-emitting dust disk, with radii sometimes exceeding a few times than the sub-mm dust disk. Similarly, as mentioned in § 2.1, multi-wavelength observations (e.g., Doi and Kataoka, 2023; Doi et al., 2024) have highlighted variations in radial structure

between dust grains of different sizes, with large grains typically being more radially confined due to radial drift. These differences suggest that the disk morphology inferred from sub-mm observations alone may not fully capture the distribution of larger, mm- to cm-sized grains, which are more sensitive to local pressure structures and dynamical evolution. This difference becomes even more pronounced in edge-on systems (Doi and Kataoka, 2023; Duchêne et al., 2024; Tazaki et al., 2025).

At present, however, VLA is the only operational facility capable of achieving sufficient sensitivity and angular resolution at cm wavelengths. A small number of disks have been successfully imaged with the VLA, including LkCa15 (Isella et al., 2014), HL Tau (Carrasco-González et al., 2016, 2019), HD 169142 (Macías et al., 2017), GM Aur (Macías et al., 2018), HD 163296 (Guidi et al., 2022), DM Tau (Liu et al., 2024), and MWC 480 (Shi et al., 2026), revealing substructures such as rings, gaps, and asymmetries at long wavelengths. These studies have provided important insights into dust growth and disk evolution, but typically require long integration times to reach the necessary sensitivity and resolution. As a result, its observational reach remains restricted to only the brightest handful of disks, limiting our ability to generalise findings across the broader disk population. This underscores the indispensable role of the SKA in the coming decade, as it will provide the capability to perform high-resolution imaging of PPDs at longer wavelengths. Compared to the VLA, the SKA will offer significantly improved sensitivity, broader frequency coverage, and a larger survey efficiency, which will enable observations of much fainter and more typical disks across different star-forming environments.

At present, however, VLA is the only operational facility capable of achieving sufficient sensitivity and angular resolution at cm wavelengths (Garufi et al., 2025). Yet, its observational reach is restricted to only the brightest handful of disks, limiting our ability to generalise findings across the broader disk population. This underscores the indispensable role of the SKA in the coming decade, as it will provide the capability to perform high-resolution imaging of PPDs at longer wavelengths. Compared to the VLA, the SKA will offer significantly improved sensitivity, broader frequency coverage, and a larger survey efficiency, which will enable observations of much fainter and more typical disks across different star-forming environments.

2.4 Frontiers in Theory and Modeling

Since the publication of *Science with the SKA* book (Braun et al., 2015) and the commissioning of ALMA, theoretical studies of planet formation and disk physics have seen substantial advances, driven in large part by the need to interpret increasingly detailed observations. Although the focus of this chapter is on substructures, we have also reviewed here several key theoretical developments over the past decade that are directly or indirectly related to them, and we hope that the next decade with the SKA will bring even more insights. One major development has been the refinement of dust evolution models that track the growth, fragmentation, radial drift, and vertical settling of grains over a wide size distribution (e.g., Birnstiel et al., 2016; Stammler et al., 2019). These models now routinely couple dust dynamics with gas disk evolution, enabling more realistic predictions of observable dust structures and their connection to underlying physical processes (see review in Birnstiel, 2024).

Simultaneously, hydrodynamical simulations incorporating embedded planets have achieved higher

spatial and temporal resolution, allowing for robust modelling of planet-disk interactions across a range of disk viscosities, aspect ratios, and thermodynamic conditions (e.g., [Dong et al., 2017](#); [Bae et al., 2017](#); [Zhang et al., 2018](#); [Harter et al., 2020](#); [Muley et al., 2021](#); [Zhang et al., 2024](#)). These efforts have demonstrated that even low-mass planets can produce prominent rings, gaps, and vortices under the right conditions, particularly in low-viscosity environments. This has narrowed the gap between observed substructures and their theoretical counterparts, providing a framework for using disk features as indirect probes of young planets.

Historically, theoretical consensus regarding angular momentum transport and accretion in PPDs has been built around turbulence-driven accretion, i.e. the classical α -model ([Shakura and Sunyaev, 1973](#)). However, the advent of ALMA has begun to challenge this paradigm. As discussed in § 2.2 and § 2.3, high-resolution and multi-wavelength observations now enable unprecedented probes of disk kinematics. Techniques such as line broadening analysis, spatially resolved gas kinematics, and statistical studies of disk evolution across large samples have been used to characterize turbulence levels (see review by [Rosotti, 2023](#)). These studies increasingly suggest that many PPD systems, especially in their planet-forming regions, which exhibit turbulence levels significantly lower than previously expected. While the specific methodologies vary, and some gas tracers probe the upper disk layers rather than the midplane, the most recent constraints place the turbulent α parameter in the range of $10^{-4} \sim 10^{-3}$ ([Flaherty et al., 2017, 2020](#)). If disks are indeed weakly turbulent or nearly inviscid, then a viable alternative mechanism must exist to account for how PPDs accrete and evolve over time. This carries profound implications, not only challenging the ubiquity of turbulence-driven accretion but also motivating the development of alternative models for disk evolution and stellar feeding.

Recent theoretical work has proposed that magnetically driven disk winds, or MHD disk winds ([Armitage et al., 2013](#); [Bai and Stone, 2013](#); [Bai, 2013](#); [Suzuki et al., 2016](#); [Bai et al., 2016](#); [Lesur, 2021](#); [Cui and Bai, 2021, 2022](#); [Tabone et al., 2025](#)), may play a dominant role in removing angular momentum from the gas, enabling accretion at rates higher than those driven by disk turbulence. Moreover, the latest 2D hydro or 3D MHD numerical simulations suggest that the presence of MHD winds can significantly alter the emergence and morphology of disk substructures compared to purely laminar disks ([Elbakyan et al., 2022](#); [Aoyama and Bai, 2023](#); [Wu et al., 2023](#); [Wafflard-Fernandez and Lesur, 2023](#); [Wu, 2024](#); [Hu et al., 2025](#)). This raises the intriguing possibility that substructure morphology may offer a straightforward observational diagnostic for identifying wind-active systems.

Recent years have also seen an expansion of planet formation theory to include the role of disk substructures themselves. Pressure bumps, zonal flows, and vortices, which once considered consequences of planet formation, are now being studied as potential precursors that facilitate pebble concentration and gravitational collapse into planetesimals ([Surville et al., 2016](#); [Taki et al., 2021](#)). In particular, the concept of "planet formation in dust traps" has gained traction, linking the spatial distribution of solids to the efficiency of core accretion and pebble accretion ([Bitsch et al., 2018](#); [Jiang and Ormel, 2023](#); [Lau et al., 2022](#)). These studies highlight how early disk conditions and substructure formation can regulate both the timing and location of planet formation.

In parallel, planet formation studies have highlighted the role of planetesimals in shaping the dust

features in PPDs (see also the Disk Demographics chapter by Garufi et al., 2026). In disks whose dust and gas are efficiently converted into planetesimals, as argued for the Solar System based on meteoritic data (Scott, 2007; Lichtenberg et al., 2023; Sirono and Turrini, 2025) — forming planets will excite their surrounding planetesimal disk on eccentric and inclined orbits and trigger a chain of dust-producing collisions (Turrini et al., 2012, 2019; Bernabò et al., 2022; Sirono and Turrini, 2025) akin to those responsible for the formation of debris disks at later stages in the life of planetary disks. These dynamical and collisional processes of the planetesimal disk imprint on the spatial distribution of cm-sized particles, injecting new dust and pebbles in disk regions that would otherwise be dust-depleted by the effects of dust traps, and creating dust sub-structures and rings in systems where multiple planets are forming (Turrini et al., 2019; Bernabò et al., 2022).

Another emerging frontier is the coupling of chemical and dynamical evolution in disk models. Time-dependent thermo-chemical codes now track how disk chemistry responds to evolving dust and gas distributions, which is crucial for interpreting molecular line emission and planet-forming environments (Eistrup et al., 2016, 2018; Booth and Ilee, 2019; Pacetti et al., 2022, 2025, see also "Disk Chemistry" chapter by Podio et al. (2026)). Such models are increasingly important for connecting observable tracers (e.g., C/H ratios, CO emissions) with hidden processes like core accretion or atmospheric recycling.

Finally, the integration of machine learning and surrogate modeling techniques has opened new possibilities for forward modeling and statistical inference. Emulators trained on large grids of hydrodynamic or radiative transfer simulations can rapidly explore parameter spaces and constrain disk or planet properties from observed features (Auddy et al., 2022; Mao et al., 2023, 2024, 2025; Ruzza et al., 2025). These developments promise to transform the interpretation of high-resolution observations in the coming decade.

In sum, the post-2014 era has marked a transition from idealized, static disk models to dynamic, multi-physics frameworks that closely mirror the complexity revealed by modern observations. The next generation of theoretical work, especially when paired with the long-wavelength capabilities of the SKA, will be critical for connecting the observed diversity of disk structures to the underlying physics of planet formation.

3 Simulated Observations & Predictions for SKA-Mid Band 5b

We can directly demonstrate the capabilities of SKA Mid for imaging known disk substructures at centimetre wavelengths. Here we can be guided by models that have been well benchmarked against high sensitivity and high angular resolution millimetre wavelength observations.¹

In this section, we demonstrate the science outcomes enabled by the SKA-Mid design baseline, Array Assembly 4 (AA4). The AA4 design baseline will consist of 133 15-m SKA dishes together with 64 13.5-m MeerKAT dishes, for a combined total of 197 dishes observing simultaneously. The SKA dishes form AA4's longest baselines along three spiral arms (achieving a maximum baseline length of 159.6 km), while the MeerKAT dishes sit at the heart of AA4. Note that, in order to carry out observations with the full integrated assembly of 197 dishes in Band 5b, specifically, the 64

¹The models and data used in this chapter are publicly available: <https://doi.org/10.7910/DVN/CNBLEH>.

MeerKAT dishes will need to be retrofitted with receivers capable of operating in Band 5b. Here we consider the AA4 design baseline to be comprised of the 133 15-m SKA dishes alone. If or when MeerKAT is equipped with Band 5b receivers, we expect that AA4 will operate with a sensitivity roughly $1.4\times$ better than our predictions in this chapter represent.²

A secondary goal of this section is to document the extent to which scientific outcomes might be achieved by the end of staged delivery (AA*), chronologically sooner than AA4. The AA* array assembly is comprised of 80 15-m SKA dishes, all equipped with Band 5b receivers. The location of one particular dish, named SKA008, contributes the longest baselines to AA*, but introduces complexities for our image-plane method (see below) for predicting AA* imaging capabilities. For details, we refer the reader to Appendix §5. In order to avoid these complexities, we consider AA* operating *without* dish SKA008. Hereafter, all references to AA* should be understood to refer to the remaining 79 15-m dishes, with a maximum baseline of 36.0 km. As above, if the 64 MeerKAT dishes with Band 5b receivers are additionally included in AA*, we expect a sensitivity boost by a factor of approximately $1.7\times$ compared to the estimates adopted in this chapter.¹

The very large number of dishes in AA4—and, to a lesser but notable extent, in AA*—will deliver exceptionally dense uv coverage, marking a genuine step change relative to existing interferometric facilities. Here, we exploit this dense sampling of the uv plane to construct SKA-Mid continuum images using an image-plane approach. We first generate model images of the expected 12.5 GHz continuum emission for a selection of known protoplanetary disks that are bright, spatially extended and structured. Our modelling of their 12.5 GHz emission is informed by their observed emission at ALMA and/or VLA frequencies. These model images are then convolved with a Gaussian kernel representing the synthesized beam, whose dimensions are found by fitting the point-spread function of uv -coverage simulated with the SKAO Observing Support Tool `ska_ost_array_config` (§3.1) or directly taken from the SKAO Sensitivity Calculator version 2.1.1 (§3.2). Correlated noise is added with an rms provided by the SKAO Sensitivity Calculator. As this procedure implicitly assumes a fully sampled uv plane, it does not capture effects associated with incomplete interferometric sampling or spatial filtering. We verified that, when integration times are sufficiently long, this image-plane method produces results comparable to full visibility-to-image simulations (e.g., Ilee et al., 2020).

The remainder of this section is structured as follows. In §3.1, we consider the HL Tau system for observations with AA* and AA4. Considering the revolutionary impact on the field made by ALMA Science Verification observations of the HL Tau disk (§2.3), this system may be a conspicuous choice for early observations with SKA-Mid. Using this system as a comparison testbed, we demonstrate the improved capabilities AA4 will provide over AA*. In §3.2, we focus on the AA4 design baseline, and present simulated SKA-Mid images of a larger sample of structured disks, working with integration times up to a 1000-hour Key Science Project (KSP). Finally, in §3.3 we describe the benefits of visibility-based analyses and advocate for the delivery of visibility data by SKAO.

²Approximating the collecting area of the 64 13.5 m MeerKAT dishes as equivalent to that of 52 15 m dishes, and considering sensitivity scales as $\sqrt{N(N-1)}$, we obtain a sensitivity boost by a factor of ≈ 1.39 for AA4, or by a factor of ≈ 1.65 for AA*.

3.1 HL Tau: A Benchmark T Tauri Star

As discussed in §2.3, the HL Tau system represents a landmark in protoplanetary disk science. ALMA’s first long-baseline images of this young T Tauri star revealed a striking system of concentric dust rings and gaps (ALMA Partnership et al., 2015), suggesting that planet formation may begin much earlier than previously anticipated, and prompting a new generation of high-angular resolution surveys that established substructure as common. Consequently, HL Tau now anchors both theoretical and observational work on planet formation, and boasts one of the most extensive, high-resolution, multi-wavelength data sets available for any protoplanetary disk (c.f. Figure 2).

Recently, Ueda et al. (2025) presented a comprehensive analysis of HL Tau’s dust disk by modelling its intensity profile observed at high angular resolution ($0.05''$ or ~ 7 au) across six wavelengths (0.45–7.9 mm) with ALMA and the VLA. With this six-wavelength dataset (shown in Figure 2) and a Markov Chain Monte Carlo (MCMC) method, they constrained six key properties of the dust grain distribution, including temperature, surface density, maximum grain size, composition, filling factor, and size distribution. Their analysis could not, however, distinguish between amorphous-carbon-rich or organics-rich dust composition (a fraction captured in their model by a f_{AC} parameter), emphasizing the need for future observations at longer wavelengths where the dust is optically thin.

Here, we employ the modeling results from Ueda et al. (2025) to generate a prediction for the radial intensity profile of the HL Tau disk at an observing wavelength of 2.4 cm, or 12.5 GHz (SKA-Mid Band 5b). Following §5.5 of Ueda et al. (2025), this model intensity profile is derived from the MCMC posterior probability distributions of the six constrained dust properties at each radial position within the disk. We optimistically assumed a dust composition rich in amorphous carbon, with $f_{AC} = 0.75\text{--}0.85$. This choice has a significant impact on the predicted long-wavelength emission: if an organics-rich composition is adopted instead, the resulting centimeter intensity can be lower by a factor of $\sim 2\text{--}3$. While the current data do not allow us to distinguish robustly between these compositions, previous disk population synthesis studies and a detailed disk modeling have suggested that an amorphous carbon-rich composition may be plausible (Delussu et al., 2024; Zagaria et al., 2025), which motivated our fiducial assumption. From the posterior probability distributions, we estimated the 68% confidence interval of the intensity at 12.5 GHz, and adopted the maximum values within this interval as the model intensity profile. We verified that this choice has only a modest effect compared with the adopted dust composition: using the minimum values within the same 68% interval changes the predicted intensity by only $\sim 15\%$. This model radial intensity profile has a native resolution of $0.05''$ inherent to the observations from which it was derived, and forms the basis for the simulated SKA-Mid observations of HL Tau presented in the remainder of this subsection.

As a first assessment of how the angular scale of the HL Tau disk’s radial substructure compares to the beam sizes accessible with SKA-Mid, and of how the predicted flux compares to the achievable sensitivity, Figure 4 shows the model radial intensity profile of the HL Tau disk at 12.5 GHz convolved to the angular resolution of AA* (79 15-m antennas) and AA4 (133 15-m antennas). The underlying model profile (in $\mu\text{Jy arcsec}^{-2}$) is scaled and spatially convolved to $\mu\text{Jy beam}^{-1}$. The beam solid angle is taken as the minor axis of a 2D Gaussian fit to the point-spread function (PSF) of the simulated uv -coverage, weighted with a Briggs robust parameter of -1 . For comparison

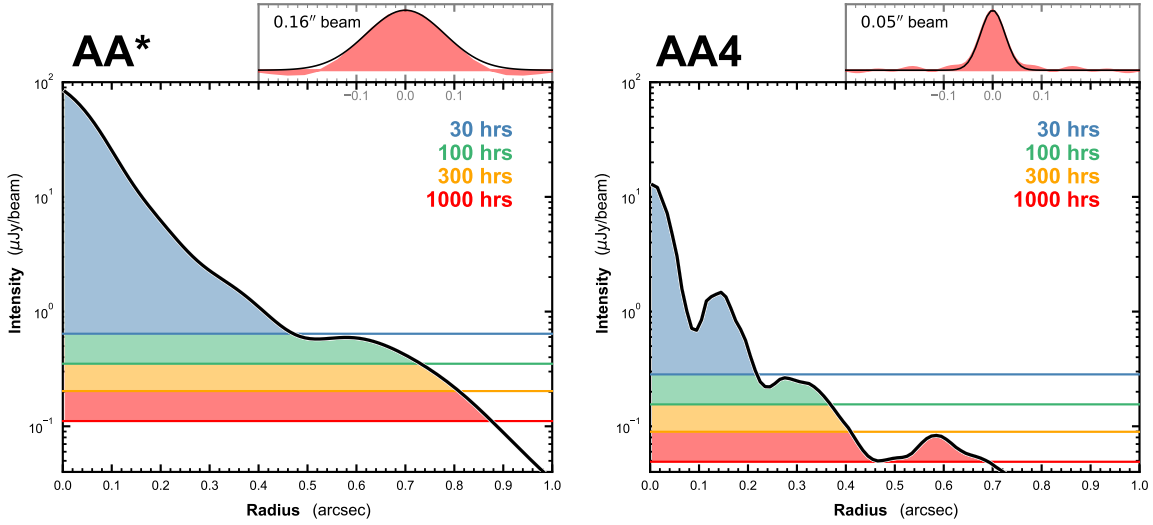


Figure 4: Predicted radial intensity profiles of the HL Tau disk at 12.5 GHz (SKA-Mid Band 5b) with AA* (left panel) and AA4 (right panel). In each panel, the underlying model profile in $\mu\text{Jy arcsec}^{-2}$ is scaled and spatially convolved to $\mu\text{Jy beam}^{-1}$, where the beam is a Gaussian fit to the PSF cross section that is shown in the top right corner. The PSFs are generated from uv -coverage simulations, and weighted with a Briggs robust parameter of -1 . Dish SKA008 is excluded from AA*. Horizontal lines show the rms noise or 1σ sensitivity achieved in 30 hours (blue), 100 hours (green), 300 hours (orange) and 1000 hours (red) of integration time. Synthetic images for the 1000 hour cases are shown in Figure 5.

with the intensity profiles, we overlay horizontal lines at the 1σ continuum sensitivity estimated by the SKAO Sensitivity Calculator for increasing integration times. Our selection of integration times is meant to represent a range between a small program and Key Science Project. We find that detecting HL Tau’s dust thermal emission with AA* requires modest integration times, while resolving its rings with AA4 requires deeper integrations.

In Figure 5, we present simulated continuum images of the HL Tau disk with AA* (79 15-m antennas) and AA4 (133 15-m antennas), using the longest integration time shown in Figure 4. The underlying sky model (presented in the left panel Fig 5) is generated by azimuthally sweeping the model radial intensity profile and projecting it onto the sky with an inclination of 46.7° and position angle of 138.0° at a distance of 147 pc (Carrasco-González et al., 2019). The sky model is convolved with a 2D Gaussian kernel representing the synthesized beam and correlated noise is added with an rms provided by the Sensitivity Calculator. We measure a flux density of approximately $85 \mu\text{Jy}$ within a $0.9'' \times 0.6''$ elliptical aperture in both images.

3.2 The SKA-Mid View of Other Structured Disks

Moving beyond a single benchmark object, we extend our SKA-Mid predictions to a broader sample of structured disk systems —J1608, DL Tau, V1094 Sco, PDS 70, HD 163296, and HD 142666— that exhibit a range of transition and ring/gap morphologies, and some systems believed have evidence on host directly imaged accreting protoplanets, like PDS 70 (Keppler et al., 2018; Wagner et al., 2018; Haffert et al., 2019) and WISPIT 2 (Close et al., 2025b). Here again our models can be anchored by high sensitivity, high angular resolution millimetre wavelength observations

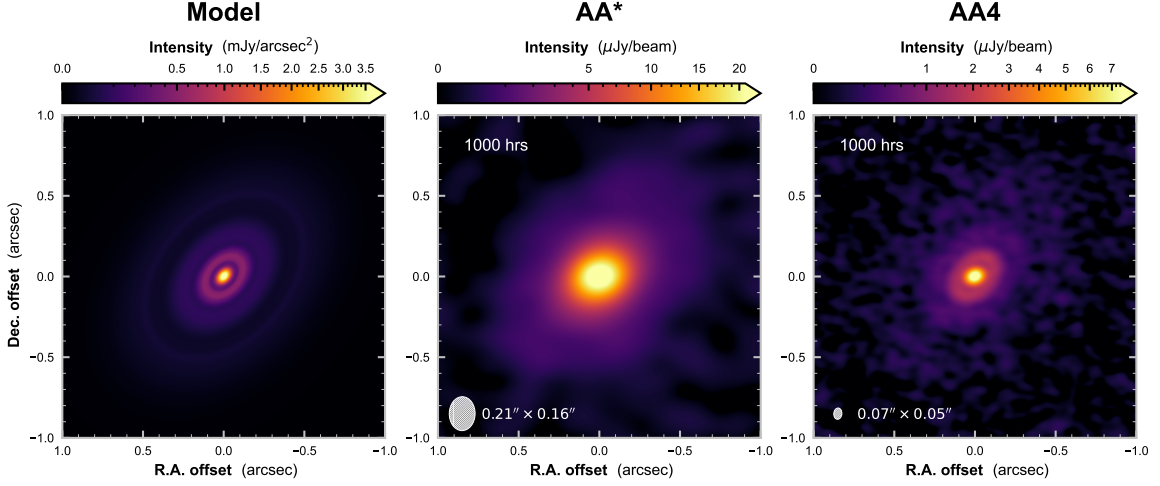


Figure 5: HL Tau through the eyes of SKA-Mid: Predicted continuum images of the HL Tau disk at 12.5 GHz (Band 5b) with AA* (middle panel) and AA4 (rightmost panel). The synthesized beams shown in the bottom left corners are generated from uv -coverage simulations, and weighted with a Briggs robust parameter of -1 . Dish SKA008 is excluded from AA*. The achieved sensitivity is $0.115 \mu\text{Jy beam}^{-1}$ and $0.049 \mu\text{Jy beam}^{-1}$ by AA* and AA4, respectively. The leftmost panel shows the underlying model in $\mu\text{Jy arcsec}^{-2}$.

with ALMA. Villenave et al. (2025) conducted a comprehensive study to reproduce millimetre observations of structured disks with ALMA using the Monte Carlo radiative transfer code `mcfostr` (Pinte et al., 2006, 2009). The models consider axisymmetric disks with a single dust grain size distribution, e.g. $n(a) \propto a^{-3.5}$, with dust grain sizes $0.005 \mu\text{m} < a < 3 \text{ mm}$ (Mathis et al., 1977). A gas-to-dust ratio of 100 is assumed to be constant across the disk, with the dust mass set to reproduce the total flux of the ALMA images. A Gaussian vertical density profile is assumed for the gas, with differential vertical dust settling set by the turbulent α parameter following Fromang and Nelson (2009). An iterative procedure was used to change the radial surface density of the model until this correctly reproduced the major axis brightness profile of the ALMA observations at either 0.8 or 1.3 mm (see also Pinte et al., 2016; Pizzati et al., 2023).

We have extended these radiative transfer calculations to predict the appearance of six of these disks at observing frequencies appropriate for SKA Mid’s Band 5b. We produce model images at a frequency of 12.5 GHz (or wavelength of 2.4 cm) using the model set-up described above. In all cases, we assume that the dust is vertically settled corresponding to $\alpha = 2 \times 10^{-3}$ but that the large and small grains are radially co-spatial. This implies no substantial radial migration of large grains has taken place, which is an appropriate assumption for highly structured disks (see, e.g., Pinilla et al., 2012b).

We then simulate the observed appearance of the models under a variety of observing conditions based on information provided by the SKAO Sensitivity Calculator (version 2.1.1). The radiative transfer models are first convolved with a Gaussian kernel of size and orientation corresponding to the synthesised beam for the requested observing conditions (assumed to lie at local zenith). This is then added to a noise field sampled from a normal distribution (convolved with the same synthesised beam) and scaled to produce an image with an rms matching the weighted continuum sensitivity

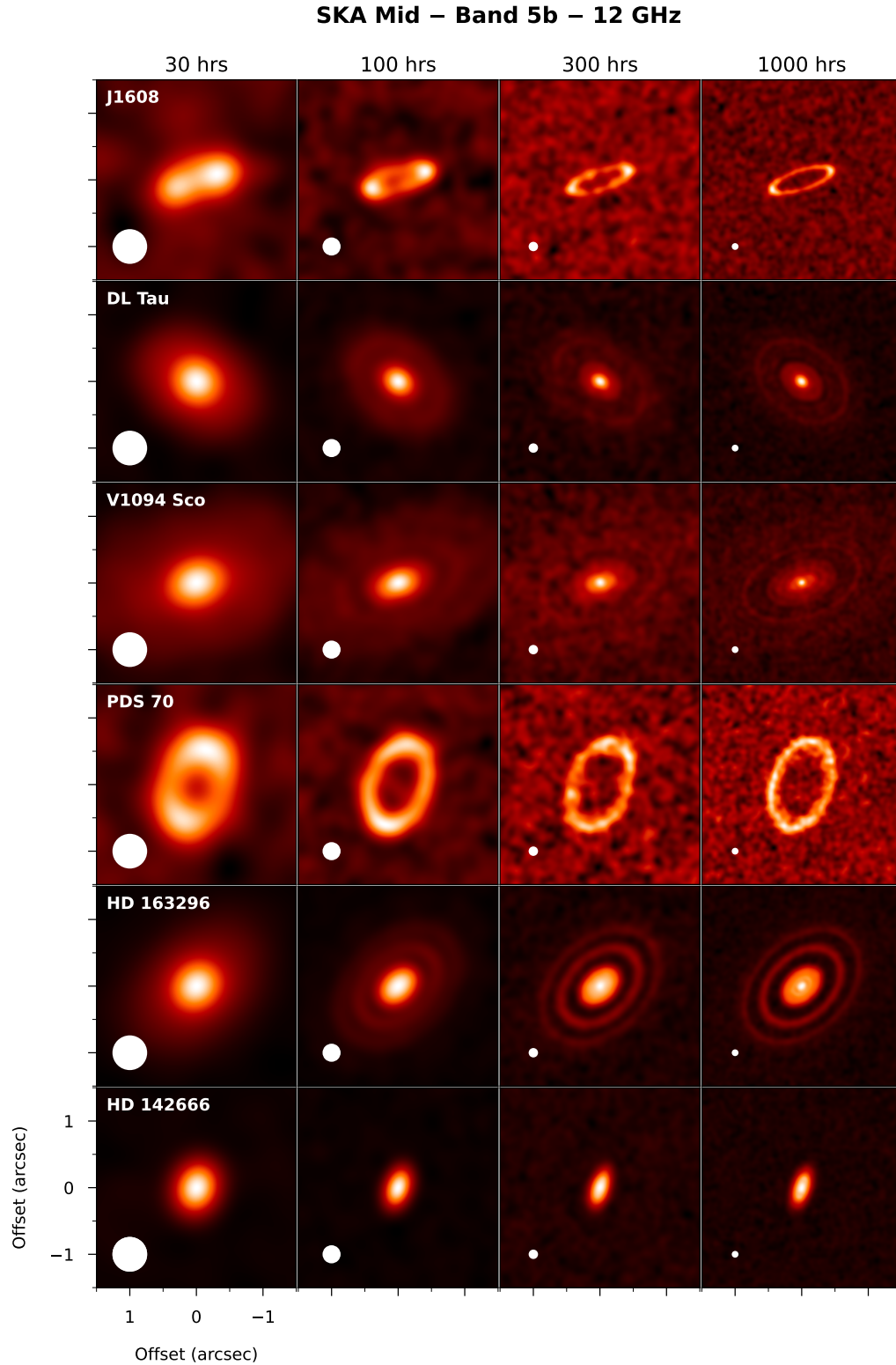


Figure 6: Simulated SKA Mid AA4 12.5 GHz observations of six protoplanetary disks with improving angular resolution ($0.5''$, $0.25''$, $0.12''$ and $0.08''$) and increasing integration time (30, 100, 300 and 1000 hrs). Each panel is peak normalised and shown with a power law stretch.

reported by the calculator (assuming a central frequency of 12 GHz and bandwidth of 5 GHz). We have verified that the results of this image plane technique are comparable to those obtained from considering a full pipeline of model visibility calculation and subsequent deconvolution (e.g. Ilee et al., 2020), while also having the advantage of being computationally much faster. This similarity is primarily due to the excellent uv -coverage of the AA4 configuration when considering the aperture synthesis of longer (≥ 12 hr) integration times. We explore a range of Briggs robust and uv -taper values that allow us to push the synthesised beam size down with increasing integration time. The results of this process are shown in Figure 6.

It is important to note that, by their design, the simulated SKA Mid observations of structured disks presented here do not include any emission from other mechanisms that may operate at SKA Mid frequencies, such as those from ionised gas. Such emission mechanisms are discussed in detail by Guidi et al. in this volume, but some are likely to be bright and compact. As such, they may introduce limitations on the achievable dynamic range for SKA Mid observations of dust continuum emission in disks. Nevertheless, multi-frequency high angular resolution observations will be required to disentangle emission from these competing mechanisms, which SKA Mid will provide.

3.3 Pushing the data to the limit: Analysing in visibility space

While facilities such as ALMA regularly provide high fidelity images of protoplanetary discs, there has been a renewed interest in modelling observations of disks directly in the native visibility plane. Such approaches offer a number of advantages over image plane deconvolution techniques. These include preserving the native spatial resolution and noise properties of the data, whilst also suppressing image reconstruction artefacts such as sidelobes and beam smearing. Tazzari et al. (2018) introduced the GALARIO code that uses GPU acceleration to speed up the computation of synthetic visibilities. GALARIO has been used to provide robust constraints on disk geometry, surface density and temperature profiles using analytic (e.g. self-similar) disk models applied to a wide range of observations of both individual disks (e.g. Clarke et al., 2018; Pinilla et al., 2021; Michel et al., 2022) and population-level studies of star forming regions such as Taurus, Orion, Ophiuchus, Lupus and Upper Scorpius (see Long et al., 2018; Sheehan et al., 2020; Tazzari et al., 2021; Vioque et al., 2025). Building on these foundations, Jennings et al. (2020) presented the frank code which uses a fast Gaussian process to directly fit observed visibilities non-parametrically and subsequently reconstruct one-dimensional radial surface brightness profiles for disks. Using this method, frank is able to achieve sub-beam resolution when compared to what would be possible with CLEAN-based imaging methods, and has been used to reveal disk substructures such as rings, gaps and asymmetries on scales as small as a few au (e.g. Jennings et al., 2022a,b; Huang et al., 2024; Ribas et al., 2024).

The application of visibility modelling to SKA Mid observations of protoplanetary disks would have many advantages. Ilee et al. (2020) demonstrated that by conducting analysis of synthetic SKA Mid visibilities, it is possible to recover structural detail in disks that would only be observable using image-plane analysis using integration times 1-2 orders of magnitude longer. Such improvements in efficiency, along with access to information on sub-beam scales, will be a powerful predictive tool as the Mid array evolves through each subsequent array assembly and operational mode. However,

there are also potential downsides. The sheer volume of raw visibility data from SKA Mid will be many orders of magnitude larger than what is routinely delivered from facilities such as ALMA. It is not clear how current visibility analysis tools would scale to such large datasets, or whether approaches based on alternative methods may be required. We therefore strongly advocate for access to calibrated visibilities during SKA Mid operations to enable the community to plan for the expansion of existing tools to exploit their analysis, ultimately enabling the highest scientific return from the observations.

4 Discussion and Summary

High angular resolution, high sensitivity observations at cm wavelengths are a crucial frontier in protoplanetary disk science. It is becoming increasingly clear that observations at mm wavelengths alone cannot resolve long-standing issues in planet formation.

When, exactly, planet formation begins remains a fundamental open question, tightly linked to the onset of observable substructure within disks. ALMA has revealed that rings, gaps, and other substructures (e.g. Fig. 1) are common in Class II systems, but high optical depths at (sub-)mm wavelengths may be masking variations in the underlying mass distribution at earlier stages, obscuring them from our detection. Long-wavelength observations are essential to break this degeneracy: if the youngest disks are genuinely smooth, rather than simply optically thick, we should see this clearly at cm wavelengths. SKA-Mid offers a route to constrain the earliest emergence of substructure, and therefore the onset of planet formation itself.

A second, closely related question is whether the bright rings we now routinely observe at mm wavelengths are sites of grain growth and planetesimal formation (and therefore the *birthplaces* of planets), or instead the signposts of planet-disk interaction (and therefore signposts of *already-formed* planets). Distinguishing between these two scenarios requires assessing the grain size distribution within the substructures (not just across the disk as a whole), which demands spatially resolved spectral index measurements inside individual rings, and –critically– parity in angular resolution across the spectral energy distribution. With SKA-Mid, we will finally achieve such parity from optical (HST) and infrared (JWST) through (sub-)mm (ALMA) to cm wavelengths. SKA-Mid will directly probe the largest grains and provide the much-needed lever arm to constrain the amount of grain growth inside these features.

Our simulated observations (§3) demonstrate SKA-Mid can resolve structured disks at cm wavelengths, but they also emphasize the need for high sensitivity – which means focusing on the brightest disks and employing long integration times. As the community begins to strategize on priority targets and design programs, a balance should be struck between broad surveys and targeted deep imaging of the brightest and most extended disk systems. Both approaches are valuable, and indeed complementary: surveys to detect cm emission from many disks will reveal evolutionary trends in true dust mass measurements across different disk populations (see also the Disk Demographics chapter by [Garufi et al., 2026](#)), while deep imaging will reveal the detailed morphology of individual exemplar disks.

The synergy between SKA, ngVLA, and ALMA will offer an unprecedented, multi-wavelength view

of protoplanetary disks (Wu et al., 2024b). Together, they combine complementary strengths in resolution, sensitivity, and wavelength coverage across spatial scales, offering the best opportunity yet to disentangle thermal dust emission from free-free processes near the central star; a key step toward characterizing the physical conditions of inner disk regions.

The SKAO’s long-term vision foresees significant expansions that would further revolutionize this field. These upgrades, previously referred to as SKA2, could include a 10-fold increase in sensitivity in wavebands up to 15 GHz, and an extension of maximum baselines to increase the angular resolution by a factor of 20. In practical terms, this means the ability to detect even fainter, optically thin dust emission at angular resolutions approaching the mas scale (e.g. from more typical, lower-mass disks).

In summary, the Square Kilometre Array will bridge a long-standing observational gap, the centimeter-wavelength blind spot, by enabling us to directly trace the growth of solids within planet-forming disks. This capability will uncover hidden stages of early planet formation, providing crucial insights into how small dust grains evolve into the building blocks of planets.

Both SKA’s high-sensitivity configurations (AA*) and its high-resolution mode (AA4) will be capable of detecting emission from centimeter-sized grains in disk substructures, precisely where planet formation seeds may be set. Beyond demographic studies (see Disk Demographics chapter), SKA will provide detailed views on individual systems, playing an essential role in characterizing the distribution and properties of cm-sized dust in protoplanetary discs.

5 Appendix

Dish SKA008 will be a part of SKA-Mid’s composition starting from the AA2 array assembly (Science Verification), and will therefore also be a part of the subsequent AA* array assembly. SKA008 is located at the furthest end of one of AA4’s spiral arms, isolated from the core of the AA* array layout. The AA* array assembly’s maximum baseline of 108.0 km is owed to SKA008’s extended location; without this dish, AA*’s maximum baseline is 36.0 km.

In Figure 7, we highlight SKA008’s contribution to the uv -coverage of AA* observations, and the resulting impact on the point-spread function (PSF). For the simplicity of this demonstration, we adopt a pointing phase center of -90.0° declination and an integration of 12 hours, such that the uv coverage and PSFs are axisymmetric. As shown in the left column of Figure 7, the PSF of AA* *without* SKA008 is approximately Gaussian. However, when dish SKA008 is included in AA* (as considered in the middle column of Figure 7), it contributes an annulus of extended uv coverage separated from that of the core. This in turn introduces non-Gaussianity and significant sidelobes within the AA* point-spread function. The right column of Figure 7 shows the PSF of AA4 is again approximately Gaussian, with its three spiral arms fully stationed.

As described in §3, we omit dish SKA008 when simulating AA* observations, as our image-plane approach assumes a Gaussian PSF. The SKAO Observing Support Tool (`ska_ost_array_config` python package) enables us to manually omit SKA008 from the AA* array layout when generating uv coverage simulations. We stress that we adopt sensitivity estimates for AA* directly from the SKAO Sensitivity Calculator, which includes SKA008 in the estimate. We have not accounted for

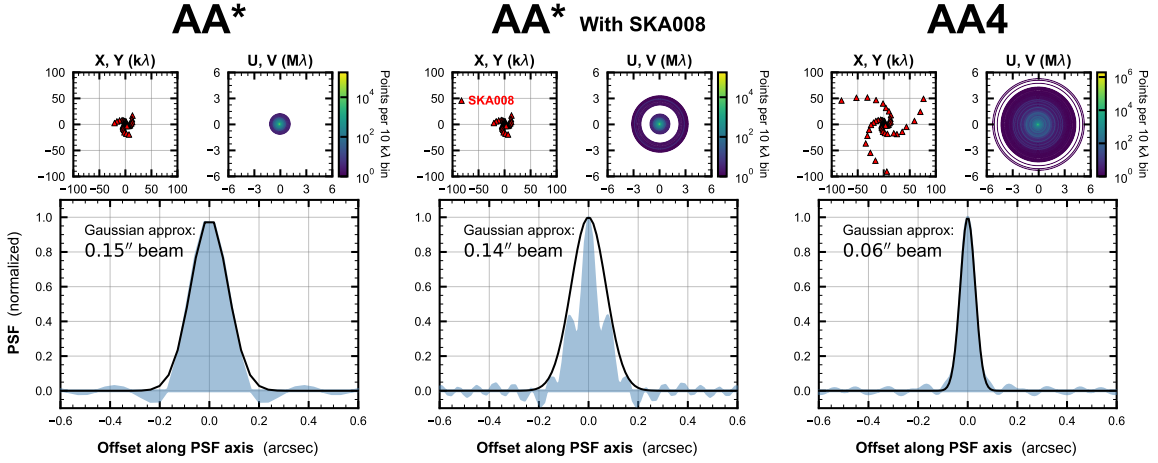


Figure 7: Comparison of array layout, simulated uv coverage, and PSF cross sections between array assemblies: AA* (left panels), AA* including dish SKA008 (middle panels) and AA4 (right panels). The uv -coverage simulations are performed with the SKAO Observing Support Tool `ska_ost_array_config` python package. The pointing phase center is taken to be the celestial south pole (-90.0° declination), such that, after the set integration time of 12 hours, the PSF has become axisymmetric. Including dish SKA008 in AA* results in a highly non-Gaussian PSF with significant sidelobes.

the discrepancy in the number of dishes (the difference between 79 and 80) nor the mis-matching beam sizes.

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References

- ALMA Partnership et al. *ApJL*, 808:L3, July 2015. doi: 10.1088/2041-8205/808/1/L3.
 S. M. Andrews. *ARA&A*, 58:483–528, Aug. 2020. doi: 10.1146/annurev-astro-031220-010302.

- S. M. Andrews et al. *ApJL*, 869(2):L41, Dec. 2018. doi: 10.3847/2041-8213/aaf741.
- M. Ansdell et al. *AJ*, 160(6):248, Dec. 2020. doi: 10.3847/1538-3881/abb9af.
- Y. Aoyama and X.-N. Bai. *ApJ*, 946(1):5, Mar. 2023. doi: 10.3847/1538-4357/acb81f.
- P. J. Armitage. *Astrophysics of Planet Formation*. 2010.
- P. J. Armitage, J. B. Simon, and R. G. Martin. *ApJL*, 778(1):L14, Nov. 2013. doi: 10.1088/2041-8205/778/1/L14.
- P. Artymowicz and S. H. Lubow. *ApJ*, 421:651–667, Feb. 1994. doi: 10.1086/173679.
- S. Auddy et al. *ApJ*, 936(1):93, Sept. 2022. doi: 10.3847/1538-4357/ac7a3c.
- B. A. Ayliffe, G. Laibe, D. J. Price, and M. R. Bate. *MNRAS*, 423(2):1450–1462, June 2012. doi: 10.1111/j.1365-2966.2012.20967.x.
- J. Bae, Z. Zhu, and L. Hartmann. *ApJ*, 850(2):201, Dec. 2017. doi: 10.3847/1538-4357/aa9705.
- J. Bae et al. In S. Inutsuka et al., editors, *Protostars and Planets VII*, volume 534 of *Astronomical Society of the Pacific Conference Series*, page 423, July 2023. doi: 10.48550/arXiv.2210.13314.
- X.-N. Bai. *ApJ*, 772(2):96, Aug. 2013. doi: 10.1088/0004-637X/772/2/96.
- X.-N. Bai and J. M. Stone. *ApJ*, 769(1):76, May 2013. doi: 10.1088/0004-637X/769/1/76.
- X.-N. Bai and J. M. Stone. *ApJ*, 796(1):31, Nov. 2014. doi: 10.1088/0004-637X/796/1/31.
- X.-N. Bai, J. Ye, J. Goodman, and F. Yuan. *ApJ*, 818(2):152, Feb. 2016. doi: 10.3847/0004-637X/818/2/152.
- M. R. Bate. *MNRAS*, 475(4):5618–5658, Apr. 2018. doi: 10.1093/mnras/sty169.
- M. R. Bate, I. A. Bonnell, and V. Bromm. *MNRAS*, 339(3):577–599, Mar. 2003. doi: 10.1046/j.1365-8711.2003.06210.x.
- M. Benisty et al. In S. Inutsuka et al., editors, *Astronomical Society of the Pacific Conference Series*, volume 534 of *Astronomical Society of the Pacific Conference Series*, page 605, July 2023.
- L. M. Bernabò et al. *ApJL*, 927(2):L22, Mar. 2022. doi: 10.3847/2041-8213/ac574e.
- J. Bi, M.-K. Lin, and R. Dong. *ApJ*, 912(2):107, May 2021. doi: 10.3847/1538-4357/abef6b.
- J. Bi, M.-K. Lin, and R. Dong. *ApJ*, 942(2):80, Jan. 2023. doi: 10.3847/1538-4357/aca1b1.
- T. Birnstiel. *ARA&A*, 62(1):157–202, Sept. 2024. doi: 10.1146/annurev-astro-071221-052705.
- T. Birnstiel, M. Fang, and A. Johansen. *Space Sci. Rev.*, 205(1-4):41–75, Dec. 2016. doi: 10.1007/s11214-016-0256-1.
- B. Bitsch et al. *A&A*, 612:A30, Apr. 2018. doi: 10.1051/0004-6361/201731931.
- J. Blum and G. Wurm. *ARA&A*, 46:21–56, Sept. 2008. doi: 10.1146/annurev.astro.46.060407.145152.
- A. J. Bohn et al. *A&A*, 658:A183, Feb. 2022. doi: 10.1051/0004-6361/202142070.
- R. A. Booth and J. D. Ilee. *MNRAS*, 487(3):3998–4011, Aug. 2019. doi: 10.1093/mnras/stz1488.
- R. Braun et al. In *Advancing Astrophysics with the Square Kilometre Array (AASKA14)*, page 174, Apr. 2015. doi: 10.22323/1.215.0174.
- C. Carrasco-González et al. *ApJL*, 821(1):L16, Apr. 2016. doi: 10.3847/2041-8205/821/1/L16.
- C. Carrasco-González et al. *ApJ*, 883(1):71, Sept. 2019. doi: 10.3847/1538-4357/ab3d33.
- A. S. Carvalho et al. *ApJ*, 971(2):129, Aug. 2024. doi: 10.3847/1538-4357/ad5a07.
- S. Casassus and S. Pérez. *ApJL*, 883(2):L41, Oct. 2019. doi: 10.3847/2041-8213/ab4425.
- S. Casassus et al. *Nature*, 493:191–194, Jan. 2013. doi: 10.1038/nature11769.
- S. Casassus et al. *ApJ*, 811(2):92, Oct. 2015. doi: 10.1088/0004-637X/811/2/92.
- P. Cassen and A. Moosman. *Icarus*, 48(3):353–376, Dec. 1981. doi: 10.1016/0019-1035(81)

- 90051-8.
- C.-Y. Chung et al. *ApJSS*, 273(2):29, Aug. 2024. doi: 10.3847/1538-4365/ad528b.
- C. J. Clarke et al. *ApJL*, 866(1):L6, Oct. 2018. doi: 10.3847/2041-8213/aae36b.
- L. M. Close et al. *AJ*, 169(1):35, Jan. 2025a. doi: 10.3847/1538-3881/ad8648.
- L. M. Close et al. *ApJL*, 990(1):L9, Sept. 2025b. doi: 10.3847/2041-8213/adf7a5.
- N. Cuello, A. Alaguero, and P. P. Poblete. *Symmetry*, 17(3):344, Feb. 2025. doi: 10.3390/sym17030344.
- C. Cui and X.-N. Bai. *MNRAS*, 507(1):1106–1126, Oct. 2021. doi: 10.1093/mnras/stab2220.
- C. Cui and X.-N. Bai. *MNRAS*, 516(3):4660–4668, Nov. 2022. doi: 10.1093/mnras/stac2580.
- P. Curone et al. *ApJL*, 984(1):L9, May 2025. doi: 10.3847/2041-8213/adc438.
- L. Delussu et al. *A&A*, 688:A81, Aug. 2024. doi: 10.1051/0004-6361/202450328.
- G. Dipierro and G. Laibe. *MNRAS*, 469(2):1932–1948, Aug. 2017. doi: 10.1093/mnras/stx977.
- G. Dipierro et al. *MNRAS*, 453(1):L73–L77, Oct. 2015. doi: 10.1093/mnrasl/slv105.
- G. Dipierro, G. Laibe, D. J. Price, and G. Lodato. *MNRAS*, 459(1):L1–L5, June 2016. doi: 10.1093/mnrasl/slw032.
- K. Doi and A. Kataoka. *ApJ*, 912(2):164, May 2021. doi: 10.3847/1538-4357/abe5a6.
- K. Doi and A. Kataoka. *ApJ*, 957(1):11, Nov. 2023. doi: 10.3847/1538-4357/acf5df.
- K. Doi et al. *ApJL*, 974(2):L25, Oct. 2024. doi: 10.3847/2041-8213/ad7f51.
- R. Dong and J. Fung. *ApJ*, 835(2):146, Feb. 2017. doi: 10.3847/1538-4357/835/2/146.
- R. Dong, Z. Zhu, R. R. Rafikov, and J. M. Stone. *ApJL*, 809:L5, Aug. 2015a. doi: 10.1088/2041-8205/809/1/L5.
- R. Dong, Z. Zhu, and B. Whitney. *ApJ*, 809(1):93, Aug 2015b. doi: 10.1088/0004-637X/809/1/93.
- R. Dong et al. *ApJ*, 823:141, June 2016. doi: 10.3847/0004-637X/823/2/141.
- R. Dong, S. Li, E. Chiang, and H. Li. *ApJ*, 843(2):127, July 2017. doi: 10.3847/1538-4357/aa72f2.
- R. Dong, S. Li, E. Chiang, and H. Li. *ApJ*, 866:110, Oct. 2018. doi: 10.3847/1538-4357/aadadd.
- D. J. D’Orazio et al. *MNRAS*, 459(3):2379–2393, July 2016. doi: 10.1093/mnras/stw792.
- B. T. Draine. *ApJ*, 636(1):1114–1120, Jan. 2006. doi: 10.1086/498130.
- B. T. Draine and H. M. Lee. *ApJ*, 285:89, Oct. 1984. doi: 10.1086/162480.
- J. Drażkowska et al. In S. Inutsuka et al., editors, *Protostars and Planets VII*, volume 534 of *Astronomical Society of the Pacific Conference Series*, page 717, July 2023. doi: 10.48550/arXiv.2203.09759.
- G. Duchêne et al. *AJ*, 167(2):77, Feb. 2024. doi: 10.3847/1538-3881/acf9a7.
- C. Eistrup, C. Walsh, and E. F. van Dishoeck. *A&A*, 595:A83, Nov. 2016. doi: 10.1051/0004-6361/201628509.
- C. Eistrup, C. Walsh, and E. F. van Dishoeck. *A&A*, 613:A14, May 2018. doi: 10.1051/0004-6361/201731302.
- V. Elbakyan, Y. Wu, S. Nayakshin, and G. Rosotti. *MNRAS*, 515(3):3113–3125, Sept. 2022. doi: 10.1093/mnras/stac1774.
- C. Espaillat et al. *Protostars and Planets VI*, pages 497–520, 2014. doi: 10.2458/azu_uapress_9780816531240-ch022.
- K. Flaherty et al. *ApJ*, 895(2):109, June 2020. doi: 10.3847/1538-4357/ab8cc5.
- K. M. Flaherty et al. *ApJ*, 843(2):150, July 2017. doi: 10.3847/1538-4357/aa79f9.
- M. Flock et al. *A&A*, 574:A68, Feb. 2015. doi: 10.1051/0004-6361/201424693.

- S. Fromang and R. P. Nelson. *A&A*, 496(3):597–608, Mar. 2009. doi: 10.1051/0004-6361/200811220.
- J. Fung and R. Dong. *ApJL*, 815(2):L21, Dec. 2015. doi: 10.1088/2041-8205/815/2/L21.
- A. Garufi et al. *A&A*, 694:A290, Feb. 2025. doi: 10.1051/0004-6361/202452496.
- A. Garufi et al. In *Advancing Astrophysics with the SKA – II (AASKAII)*. 2026. arXiv search: Report number "AASKAII/Garufi01".
- O. M. Guerra-Alvarado et al. *A&A*, 686:A298, June 2024. doi: 10.1051/0004-6361/202349046.
- G. Guidi et al. *A&A*, 664:A137, Aug. 2022. doi: 10.1051/0004-6361/202142303.
- G. Guidi et al. In *Advancing Astrophysics with the SKA – II (AASKAII)*. 2026. arXiv search: Report number "AASKAII/Guidi01".
- S. Y. Haffert et al. *Nature Astronomy*, 3:749–754, June 2019. doi: 10.1038/s41550-019-0780-5.
- S. K. Harter, L. Ricci, S. Zhang, and Z. Zhu. *ApJ*, 905(1):24, Dec. 2020. doi: 10.3847/1538-4357/abcafc.
- J. Hashimoto et al. *ApJ*, 911(1):5, Apr. 2021. doi: 10.3847/1538-4357/abe59f.
- M. Hoare et al. In *Advancing Astrophysics with the Square Kilometre Array (AASKA14)*, page 115, Apr. 2015. doi: 10.22323/1.215.0115.
- F. Hoyle. *ApJ*, 118:513, Nov. 1953. doi: 10.1086/145780.
- C.-H. Hsieh et al. *A&A*, 700:A235, Aug. 2025. doi: 10.1051/0004-6361/202555174.
- X. Hu, Z.-Y. Li, J. Bae, and Z. Zhu. *MNRAS*, 536(2):1374–1388, Jan. 2025. doi: 10.1093/mnras/stae2681.
- J. Huang et al. *ApJL*, 869(2):L43, Dec. 2018. doi: 10.3847/2041-8213/aaf7a0.
- J. Huang et al. *ApJ*, 976(1):132, Nov. 2024. doi: 10.3847/1538-4357/ad84df.
- J. D. Ilee et al. *MNRAS*, 498(4):5116–5127, Nov. 2020. doi: 10.1093/mnras/staa2699.
- A. Isella et al. *ApJ*, 788(2):129, June 2014. doi: 10.1088/0004-637X/788/2/129.
- J. Jennings et al. *MNRAS*, 495(3):3209–3232, July 2020. doi: 10.1093/mnras/staa1365.
- J. Jennings et al. *MNRAS*, 509(2):2780–2799, Jan. 2022a. doi: 10.1093/mnras/stab3185.
- J. Jennings et al. *MNRAS*, 514(4):6053–6073, Aug. 2022b. doi: 10.1093/mnras/stac1770.
- H. Jiang and C. W. Ormel. *MNRAS*, 518(3):3877–3900, Jan. 2023. doi: 10.1093/mnras/stac3275.
- S. Jin et al. *ApJ*, 818(1):76, Feb. 2016. doi: 10.3847/0004-637X/818/1/76.
- A. Johansen and M. Lambrechts. *Annual Review of Earth and Planetary Sciences*, 45(1):359–387, Aug. 2017. doi: 10.1146/annurev-earth-063016-020226.
- A. Johansen et al. *Nature*, 448(7157):1022–1025, Aug. 2007. doi: 10.1038/nature06086.
- K. D. Kanagawa, H. Tanaka, T. Muto, and T. Tanigawa. *PASJ*, 69(6):97, Dec. 2017. doi: 10.1093/pasj/psx114.
- K. D. Kanagawa, H. Tanaka, and E. Szuszkiewicz. *ApJ*, 861(2):140, July 2018. doi: 10.3847/1538-4357/aac8d9.
- S. J. Kenyon and L. Hartmann. *ApJ*, 323:714, Dec. 1987. doi: 10.1086/165866.
- M. Keppler et al. *A&A*, 617:A44, Sept. 2018. doi: 10.1051/0004-6361/201832957.
- W. Kley and R. P. Nelson. *ARA&A*, 50:211–249, Sept. 2012. doi: 10.1146/annurev-astro-081811-125523.
- C. J. Lada and E. A. Lada. *ARA&A*, 41:57–115, Jan. 2003. doi: 10.1146/annurev.astro.41.011802.094844.
- M. Lambrechts and A. Johansen. *A&A*, 544:A32, Aug. 2012. doi: 10.1051/0004-6361/201219127.

- R. B. Larson. *MNRAS*, 194:809–826, Mar. 1981. doi: 10.1093/mnras/194.4.809.
- T. C. H. Lau et al. *A&A*, 668:A170, Dec. 2022. doi: 10.1051/0004-6361/202244864.
- G. R. J. Lesur. *A&A*, 650:A35, June 2021. doi: 10.1051/0004-6361/202040109.
- R. Li, A. N. Youdin, and J. B. Simon. *ApJ*, 885(1):69, Nov. 2019. doi: 10.3847/1538-4357/ab480d.
- T. Lichtenberg, L. K. Schaefer, M. Nakajima, and R. A. Fischer. In S. Inutsuka et al., editors, *Protostars and Planets VII*, volume 534 of *Astronomical Society of the Pacific Conference Series*, page 907, July 2023. doi: 10.48550/arXiv.2203.10023.
- D. N. C. Lin and J. Papaloizou. *MNRAS*, 191:37–48, Apr. 1980. doi: 10.1093/mnras/191.1.37.
- H. B. Liu et al. *A&A*, 685:A18, May 2024. doi: 10.1051/0004-6361/202348896.
- F. Long et al. *ApJ*, 869(1):17, Dec. 2018. doi: 10.3847/1538-4357/aae8e1.
- D. Lynden-Bell and J. E. Pringle. *MNRAS*, 168:603–637, Sept. 1974. doi: 10.1093/mnras/168.3.603.
- M.-M. Mac Low and R. S. Klessen. *Reviews of Modern Physics*, 76(1):125–194, Jan. 2004. doi: 10.1103/RevModPhys.76.125.
- E. Macías et al. *ApJ*, 838(2):97, Apr. 2017. doi: 10.3847/1538-4357/aa6620.
- E. Macías et al. *ApJ*, 865(1):37, Sept. 2018. doi: 10.3847/1538-4357/aad811.
- E. Macías et al. *ApJ*, 881(2):159, Aug. 2019. doi: 10.3847/1538-4357/ab31a2.
- C. F. Manara et al. In S. Inutsuka et al., editors, *Protostars and Planets VII*, volume 534 of *Astronomical Society of the Pacific Conference Series*, page 539, July 2023. doi: 10.48550/arXiv.2203.09930.
- S. Mao et al. *ApJL*, 950(2):L12, June 2023. doi: 10.3847/2041-8213/acd77f.
- S. Mao et al. *ApJ*, 976(2):200, Dec. 2024. doi: 10.3847/1538-4357/ad8086.
- S. Mao et al. *ApJL*, 992(2):L20, Oct. 2025. doi: 10.3847/2041-8213/ae0b60.
- S. Marino, S. Perez, and S. Casassus. *ApJL*, 798:L44, Jan. 2015. doi: 10.1088/2041-8205/798/2/L44.
- J. S. Mathis, W. Rumpl, and K. H. Nordsieck. *ApJ*, 217:425–433, Oct. 1977. doi: 10.1086/155591.
- M. J. Moreira et al. *A&A*, 689:L5, Sept. 2024. doi: 10.1051/0004-6361/202451166.
- M. J. Moreira et al. *arXiv e-prints*, art. arXiv:2510.19635, Oct. 2025. doi: 10.48550/arXiv.2510.19635.
- M. J. Moreira et al. *A&A*, 705:A96, Jan. 2026. doi: 10.1051/0004-6361/202556063.
- W. H. McCrea. *Proceedings of the Royal Society of London Series A*, 256(1285):245–266, June 1960. doi: 10.1098/rspa.1960.0108.
- A. Michel et al. *ApJ*, 937(2):104, Oct. 2022. doi: 10.3847/1538-4357/ac905c.
- D. Muley, R. Dong, and J. Fung. *AJ*, 162(4):129, Oct. 2021. doi: 10.3847/1538-3881/ac141f.
- K. I. Öberg et al. *ApJSS*, 257(1):1, Nov. 2021. doi: 10.3847/1538-4365/ac1432.
- K. I. Öberg, S. Facchini, and D. E. Anderson. *ARA&A*, 61:287–328, Aug. 2023. doi: 10.1146/annurev-astro-022823-040820.
- N. Ohashi et al. *ApJ*, 951(1):8, July 2023. doi: 10.3847/1538-4357/acd384.
- S. Okuzumi et al. *ApJ*, 821(2):82, Apr. 2016. doi: 10.3847/0004-637X/821/2/82.
- C. W. Ormel and H. H. Klahr. *A&A*, 520:A43, Sept. 2010. doi: 10.1051/0004-6361/201014903.
- S. Paardekooper et al. In S. Inutsuka et al., editors, *Protostars and Planets VII*, volume 534 of *Astronomical Society of the Pacific Conference Series*, page 685, July 2023. doi: 10.48550/arXiv.2203.09595.

- E. Pacetti et al. *ApJ*, 937(1):36, Sept. 2022. doi: 10.3847/1538-4357/ac8b11.
- E. Pacetti et al. *A&A*, 701:A194, Sept. 2025. doi: 10.1051/0004-6361/202554012.
- S. Perez et al. *ApJL*, 811(1):L5, Sept. 2015. doi: 10.1088/2041-8205/811/1/L5.
- S. Pérez, S. Casassus, and P. Benítez-Llambay. *MNRAS*, 480(1):L12–L17, Oct. 2018. doi: 10.1093/mnras/sly109.
- S. Pérez et al. *AJ*, 158(1):15, July 2019. doi: 10.3847/1538-3881/ab1f88.
- P. Pinilla, M. Benisty, and T. Birnstiel. *A&A*, 545:A81, Sept. 2012a. doi: 10.1051/0004-6361/201219315.
- P. Pinilla et al. *A&A*, 538:A114, Feb 2012b. doi: 10.1051/0004-6361/201118204.
- P. Pinilla et al. *A&A*, 649:A122, May 2021. doi: 10.1051/0004-6361/202140371.
- C. Pinte, F. Ménard, G. Duchêne, and P. Bastien. *A&A*, 459(3):797–804, Dec. 2006. doi: 10.1051/0004-6361:20053275.
- C. Pinte et al. *A&A*, 498(3):967–980, May 2009. doi: 10.1051/0004-6361/200811555.
- C. Pinte et al. *ApJ*, 816(1):25, Jan. 2016. doi: 10.3847/0004-637X/816/1/25.
- C. Pinte et al. *ApJL*, 860(1):L13, June 2018. doi: 10.3847/2041-8213/aac6dc.
- C. Pinte et al. *Nature Astronomy*, 3:1109–1114, Aug. 2019. doi: 10.1038/s41550-019-0852-6.
- C. Pinte et al. *ApJL*, 890(1):L9, Feb. 2020. doi: 10.3847/2041-8213/ab6dda.
- C. Pinte et al. *MNRAS*, 526(1):L41–L46, Nov. 2023. doi: 10.1093/mnras/slاد010.
- C. Pinte et al. *ApJL*, 984(1):L15, May 2025. doi: 10.3847/2041-8213/adc433.
- E. Pizzati, G. P. Rosotti, and B. Tabone. *MNRAS*, 524(2):3184–3200, Sept. 2023. doi: 10.1093/mnras/stad2057.
- L. Podio et al. In *Advancing Astrophysics with the SKA – II (AASKAII)*. 2026. arXiv search: Report number "AASKAII/Podio01".
- J. E. Pringle. *ARA&A*, 19:137–162, Jan. 1981. doi: 10.1146/annurev.aa.19.090181.001033.
- B. Ren et al. *ApJL*, 857:L9, Apr. 2018. doi: 10.3847/2041-8213/aab7f5.
- Á. Ribas, C. J. Clarke, and F. Zagaria. *MNRAS*, 532(2):1752–1764, Aug. 2024. doi: 10.1093/mnras/stae1534.
- Á. Ribas et al. *Nature Astronomy*, 9:1176–1183, Aug. 2025. doi: 10.1038/s41550-025-02576-w.
- K. A. Rosenfeld, E. Chiang, and S. M. Andrews. *ApJ*, 782(2):62, Feb. 2014. doi: 10.1088/0004-637X/782/2/62.
- G. P. Rosotti. *New Astron. Rev.*, 96:101674, June 2023. doi: 10.1016/j.newar.2023.101674.
- G. P. Rosotti et al. *MNRAS*, 491(1):1335–1347, Jan. 2020. doi: 10.1093/mnras/stz3090.
- S. P. Ruden and D. N. C. Lin. *ApJ*, 308:883, Sept. 1986. doi: 10.1086/164559.
- A. Ruzza, G. Lodato, G. P. Rosotti, and P. J. Armitage. *arXiv e-prints*, art. arXiv:2506.11200, June 2025. doi: 10.48550/arXiv.2506.11200.
- E. R. D. Scott. *Annual Review of Earth and Planetary Sciences*, 35(1):577–620, May 2007. doi: 10.1146/annurev.earth.35.031306.140100.
- D. M. Segura-Cox et al. *Nature*, 586(7828):228–231, Oct. 2020. doi: 10.1038/s41586-020-2779-6.
- D. Semenov et al. *A&A*, 410:611–621, Nov. 2003. doi: 10.1051/0004-6361:20031279.
- N. I. Shakura and R. A. Sunyaev. *A&A*, 24:337–355, Jan. 1973.
- P. D. Sheehan and J. A. Eisner. *ApJ*, 857(1):18, Apr 2018. doi: 10.3847/1538-4357/aaae65.
- P. D. Sheehan et al. *ApJ*, 902(2):141, Oct. 2020. doi: 10.3847/1538-4357/abbad5.
- Y. Shi et al. *ApJ*, 966(1):59, May 2024. doi: 10.3847/1538-4357/ad2e94.

- Y. Shi et al. *arXiv e-prints*, art. arXiv:2602.19941, Feb. 2026. doi: 10.48550/arXiv.2602.19941.
- A. Sierra et al. *ApJ*, 974(2):306, Oct. 2024. doi: 10.3847/1538-4357/ad7460.
- S.-i. Sirono and D. Turrini. *Scientific Reports*, 15(1):30919, Aug. 2025. doi: 10.1038/s41598-025-12643-x.
- J. Speedie and R. Dong. *ApJL*, 940(2):L43, Dec. 2022. doi: 10.3847/2041-8213/aca074.
- J. Speedie, R. A. Booth, and R. Dong. *ApJ*, 930(1):40, May 2022. doi: 10.3847/1538-4357/ac5cc0.
- J. Speedie et al. *Nature*, 633(8028):58–62, Sept. 2024. doi: 10.1038/s41586-024-07877-0.
- J. Stadler et al. *A&A*, 670:L1, Feb. 2023. doi: 10.1051/0004-6361/202245381.
- S. M. Stammler et al. *ApJL*, 884(1):L5, Oct. 2019. doi: 10.3847/2041-8213/ab4423.
- Z. Su and X.-N. Bai. *ApJ*, 975(1):126, Nov. 2024. doi: 10.3847/1538-4357/ad7581.
- C. Surville, L. Mayer, and D. N. C. Lin. *ApJ*, 831(1):82, Nov. 2016. doi: 10.3847/0004-637X/831/1/82.
- T. K. Suzuki et al. *A&A*, 596:A74, Dec. 2016. doi: 10.1051/0004-6361/201628955.
- B. Tabone et al. *ApJ*, 989(1):7, Aug. 2025. doi: 10.3847/1538-4357/adc7b1.
- T. Taki, K. Kuwabara, H. Kobayashi, and T. K. Suzuki. *ApJ*, 909(1):75, Mar. 2021. doi: 10.3847/1538-4357/abd79f.
- Y.-W. Tang et al. *ApJ*, 840(1):32, May 2017. doi: 10.3847/1538-4357/aa6af7.
- R. Tazaki et al. *ApJ*, 980(1):49, Feb. 2025. doi: 10.3847/1538-4357/ad9c6f.
- M. Tazzari, F. Beaujean, and L. Testi. *MNRAS*, 476(4):4527–4542, June 2018. doi: 10.1093/mnras/sty409.
- M. Tazzari et al. *MNRAS*, 506(4):5117–5128, Oct. 2021. doi: 10.1093/mnras/stab1912.
- R. Teague et al. *ApJL*, 984(1):L6, May 2025. doi: 10.3847/2041-8213/adc43b.
- D. Turrini, A. Coradini, and G. Magni. *ApJ*, 750(1):8, May 2012. doi: 10.1088/0004-637X/750/1/8.
- D. Turrini, F. Marzari, D. Polychroni, and L. Testi. *ApJ*, 877(1):50, May 2019. doi: 10.3847/1538-4357/ab18f5.
- T. Ueda et al. *ApJ*, 990(2):183, Sept. 2025. doi: 10.3847/1538-4357/adf214.
- R. F. van Capelleveen et al. *ApJL*, 990(1):L8, Sept. 2025. doi: 10.3847/2041-8213/adf721.
- N. van der Marel et al. *Science*, 340:1199–1202, 2013.
- N. van der Marel et al. *ApJ*, 872(1):112, Feb. 2019. doi: 10.3847/1538-4357/aafd31.
- N. van der Marel et al. *AJ*, 161(1):33, Jan. 2021. doi: 10.3847/1538-3881/abc3ba.
- M. Villenave et al. *A&A*, 642:A164, Oct. 2020. doi: 10.1051/0004-6361/202038087.
- M. Villenave et al. *ApJ*, 930(1):11, May 2022. doi: 10.3847/1538-4357/ac5fae.
- M. Villenave et al. *ApJ*, 961(1):95, Jan. 2024. doi: 10.3847/1538-4357/ad0c4b.
- M. Villenave et al. *A&A*, 697:A64, May 2025. doi: 10.1051/0004-6361/202553822.
- M. Vioque et al. *ApJ*, 989(1):9, Aug. 2025. doi: 10.3847/1538-4357/adc7b0.
- G. Wafflard-Fernandez and G. Lesur. *A&A*, 677:A70, Sept. 2023. doi: 10.1051/0004-6361/202245305.
- K. Wagner et al. *ApJL*, 863(1):L8, Aug. 2018. doi: 10.3847/2041-8213/aad695.
- K. Wagner et al. *Nature Astronomy*, 7:1208–1217, Oct. 2023. doi: 10.1038/s41550-023-02028-3.
- S. J. Weidenschilling. *MNRAS*, 180:57–70, July 1977. doi: 10.1093/mnras/180.1.57.
- J. P. Williams and L. A. Cieza. *ARA&A*, 49:67–117, Sept. 2011. doi: 10.1146/annurev-astro-081710-102548.
- Y. Wu. *ApJ*, 970(1):25, July 2024. doi: 10.3847/1538-4357/ad5553.

- Y. Wu et al. *MNRAS*, 523(2):2630–2640, Aug. 2023. doi: 10.1093/mnras/stad1553.
- Y. Wu et al. *ApJ*, 962(173):173, Feb. 2024a. doi: 10.3847/1538-4357/ad15fe.
- Y. Wu, S.-F. Liu, H. Jiang, and S. Nayakshin. *ApJ*, 965(2):110, Apr. 2024b. doi: 10.3847/1538-4357/ad323b.
- L. Yang et al. *ApJ*, 989(2):176, Aug. 2025. doi: 10.3847/1538-4357/adf0fa.
- A. N. Youdin and J. Goodman. *ApJ*, 620(1):459–469, Feb. 2005. doi: 10.1086/426895.
- F. Zagaria, G. P. Rosotti, R. D. Alexander, and C. J. Clarke. *European Physical Journal Plus*, 138(1):25, Jan. 2023. doi: 10.1140/epjp/s13360-022-03616-4.
- F. Zagaria et al. *A&A*, 702:A56, Oct. 2025. doi: 10.1051/0004-6361/202452986.
- K. Zhang, G. A. Blake, and E. A. Bergin. *ApJL*, 806(1):L7, June 2015. doi: 10.1088/2041-8205/806/1/L7.
- K. Zhang et al. *arXiv e-prints*, art. arXiv:2506.10719, June 2025. doi: 10.48550/arXiv.2506.10719.
- M. Zhang, P. Huang, and R. Dong. *ApJ*, 961(1):86, Jan. 2024. doi: 10.3847/1538-4357/ad055c.
- S. Zhang et al. *ApJL*, 869(2):L47, Dec. 2018. doi: 10.3847/2041-8213/aaf744.
- Z. Zhu, R. Dong, J. M. Stone, and R. R. Rafikov. *ApJ*, 813(2):88, Nov. 2015. doi: 10.1088/0004-637X/813/2/88.
- A. Zurlo, R. Gratton, S. Pérez, and L. Cieza. *European Physical Journal Plus*, 138(5):411, May 2023. doi: 10.1140/epjp/s13360-023-04041-x.