Substructures in the Protostellar Phase: Connection to Planet Formation

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Abstract

Recent millimeter/submillimeter surveys have suggested that substructures, such as rings/gaps, spiral arms, and cavities, ubiquitously exist in protoplanetary disks. Substructures have also been detected in several younger disks, i.e. protostellar disks. If they are indicatives of planets within the disks, the observations may show planet formation begins at the disk-forming stage, contrary to the classical planet formation scenario. Origins and ubiquity of substructures remain unclear especially for protostellar sources, Investigation is necessary to update our current understandings of stellar system formation. Deeply embedded nature and expectedly small sizes (of the order of $\sim 10\,\mathrm{au}$) of protostellar disks require high-resolution radio observations to find/resolve substructures and to study the origins and detailed properties. The next-generation VLA is a unique facility that can make such investigations feasible owing to the frequency coverage, angular resolutions, and sensitivity.

1. Introduction

Star formation begins with gravitational collapse in overdense regions of molecular clouds. The 0.1–$1\,\mathrm{pc}$ scale star-forming dense cores/clumps were manifested as dark patches at visible bands owning to the high dust extinction. The development of the infrared observing techniques has enabled penetrating into these dense cores/clumps, to investigate the embedded young stellar objects (YSOs). In particular, the extremely high angular resolution (e.g., 30–$100\,\mathrm{mas}$, ~ 4.5–$15\,\mathrm{au}$) infrared imaging observations with the 8–10 meter telescopes (e.g., Subaru/HiCIAO, VLT/SPHERE, Gemini/GPI, etc) have resolved rich sub-structures, such as arcs and spiral arms, in the naked protoplanetary disks (namely Class II disks), and have detected gas giants around the naked young stars (namely Class III objects) and in one protoplanetary disk, PDS 70 (Keppler et al. 2018). These studies have attracted significant interest in the studies about extra-solar planet formation, and about planet-disk interaction.

Most of the Class II disks are optically thick at the infrared bands such that infrared imaging observations only traced the scattered light from the disk surface. The timely development of the Atacama Large Millimeter/submillimeter Array (ALMA) has permitted resolving the dense structures at the disk midplane with a similar angular resolution with the aforementioned infrared facilities, providing a strong synergy. The ALMA observations have revealed that substructures, such as rings, gaps, and spirals, are frequently found in the dust distributions of protoplanetary disks (Andrews et al. 2018). It indicates that having substructures is likely a ubiquitous feature for planet-forming disks in Class II objects.

Theoretical works (e.g., Goldreich & Tremaine 1980) successfully explain substructure formation with massive planets curving gaps by exerting torques to their parental disks, although consensus has yet to be reached regarding the formation mechanisms. On one hand, the disk substructures ubiquitously resolved by ALMA observations towards the Class II disk may be compatible with the results of the NASA Kepler mission, which has concluded that (super-)Earths are extremely common. On the other hand, it may also indicate that substructures and/or exoplanets have formed prior to the Class II phase, instead of being formed during or after the Class II phase. This is supported by some recent ALMA observations which resolved substructures in the embedded, Class I disks (e.g., Sheehan & Eisner 2017; Sheehan & Eisner 2018; Segura-Cox et al. 2020). In an even younger (Class 0) source, L1527, where the embedded protostars are not visible from infrared observations, the recent high angular resolution JVLA observations at 7 mm wavelength also resolved substructures (Nakatani et al. 2020). If the substructures are indicative of forming planets within the disks, these observational results are the evidence planet formation commences by an order of magnitude earlier than has been predicted by the classical planet formation scenario. These observational findings require updates to our current understandings. However, extending the high-resolution dust continuum imaging to more Class 0 sources remains difficult since (1) ALMA observations are subject to the too-high optical depth, and (2) both JVLA and ALMA observations (e.g., at 3–$10\,\mathrm{mm}$ wavelengths) are yet limited by sensitivity and angular resolution.

The natural questions coming next would be “Do substructures also from in even younger objects?”, “Are substructures also ubiquitous among Class 0/I disks?”, and “How and when those substructures were formed? Is it due to planets or others?”. It is of particular interest whether they are signatures of protoplanets within disks; if so, it implies formation of protostar, protostellar disk, and protoplanet may actually occur at the same time, which is again beyond expectation of the classical planet formation scenario. Answering these open questions would be matter of discussions in next decade(s), which will require longer wavelength and higher angular resolution observations to penetrate into the more deeply embedded regions in the circumstellar disks. The capability of the ngVLA is ideal for this purpose. We note that prior to the well-known ALMA long baseline image towards the Class II disk, HL Tau, one would hardly expect the rich disk substructures. With the unprecedented angular resolution and sensitivity of the ngVLA, we will also likely discover unexpected detail patterns internal or external to the sub-structures. These may either help constrain the formation mechanisms of substructures or may open new research fields. Studying substructure formation in the protostellar phase is an indispensable piece to solve the puzzles and to construct a next-generation formation scenario of stellar systems, which will be very complementary to the 30-meter class optical/infrared observations towards exoplanets.

2. Observations towards Protostellar Disks

Protostar-disk systems are embedded in a large-scale dense envelope. It can make the emission significantly obscured even at near-infrared wavelengths for Class 0 sources. Longer wavelength observations, namely millimeter/submillimeter and radio observations, are thus essential to study the structures of protostellar disks.

2.1. *Disk mass and radius*

Recently large surveys have been conducted towards Class 0 and I sources using ALMA and The Karl G. Jansky Very Large Array (JVLA). Segura-Cox et al. (2016); Segura-Cox et al. (2018) have performed millimeter observations towards protostars in the Perseus molecular cloud with a high angular resolution ($\sim 0.''07$) in a part of the VLA/ALMA Nascent Disk and Multiplicity (VANDAM) survey and found protostellar disk candidates for 18 Class 0 objects. Typical disk radii are estimated to be $< 30\,\mathrm{au}$, which is systematically smaller than those of Class II disks as expected. Tobin et al. (2020) have conducted the VANDAM survey towards 328 protostars in the Orion A and B molecular clouds with angular resolutions of $\sim 0.''1$ ($40\,\mathrm{au}$) at $0.87\,\mathrm{mm}$ (ALMA Band 7) and $\sim 0.''08$ ($32\,\mathrm{au}$) at $9\,\mathrm{mm}$ (JVLA Ka Band). Average dust disk mass and radii have been measured for each of Class 0, I, and flat-spectrum sources. Interestingly, the measured radii ($\approx 45, 37, 29\,\mathrm{au}$, respectively) as well as the measured mass shows a systematic *decrease* with the system evolution (see also the discussions in Liu 2020 for the mass). This may point out that the dust disk radius does not necessarily grow during the protostellar phase.

Clearly, for further investigation on the statistics of disk mass and radius, future large-sample, multiband surveys are needed with a higher-angular resolution so that the small sizes of protostellar disks are well resolved. At the same time, mass sensitivity is required to be sufficiently high.

2.2. *Substructures*

Radio and millimeter/submillimeter observations by ALMA and JVLA have detected ring, gap, spiral arm structures in several Class I disks: e.g., V883 Ori (Cieza et al. 2016), WL17 (Sheehan & Eisner 2017), GY91 (Sheehan & Eisner 2018), HH 111 (Lee et al. 2019), and IRS 63 (Segura-Cox et al. 2020). Substructure has also found in an even younger Class 0/I object, L1527 IRS (Nakatani et al. 2020; see the right panel of Figure 1 showing the detected substructure of L1527 IRS for reference.) These findings as well as those in previous observational works regrading dust substructures can be summarized as Table 1. A recent ALMA survey, the Disk Substructures at High Angular Resolution Project (e.g., DSHARP; Andrews et al. 2018), has targeted 20 Class II objects and has found substructures in all of the targets. The results indicate that substructures are likely ubiquitous among protoplanetary disks. Now it is known substructures also exist at least some of Class 0/I sources as mentioned above, yet the ubiquity remains unclear. Currently, the existence of substructures in Class 0 objects is supported only by the observational results for L1527 IRS mostly because of limited spatial resolutions achieved by the currently available facilities. We note, however, that the geometry of the L1517's substructure has not yet been identified. It can be ring(s), spirals, or localized gas/dust clumps (e.g., vortices and pressure bumps). The characters of substructures, such as ubiquity and geometry, in Class 0 objects are even less understood compared to Class I/II objects.

Table 1. Current understandings regarding substructures

	Existence	Ubiquity
Class 0	Yes	unknown
Class I	Yes	unknown
Class II	Yes	likely

Theoretical studies have proposed many formation mechanisms of the observed ring/gap, cavity, spiral arms, and crescent patterns: disk-planet interaction (e.g., Goldreich & Tremaine 1980), Rossby wave instability (e.g., Lovelace et al. 1999), photoevaporation (e.g., Clarke et al. 2001), baloclinic instability (e.g., Klahr & Bodenheimer 2003), gravitational instability (e.g., Rice et al. 2004), secular gravitational instability (Youdin 2011; Takahashi & Inutsuka 2014) MHD zonal flows (e.g., Uribe et al. 2011), MHD winds (e.g., Suzuki et al. 2016), vertical shear instability (e.g., Richard et al. 2016), sintering (Okuzumi et al. 2016), sublimation at snow lines (Stammler et al. 2017) molecular bond effects (Pinilla et al. 2017), growth front (Ohashi et al. 2020). The underlying physics of these mechanisms are hydrodynamics effects, grain growth, dust-gas interactions, and/or dynamical interaction with companions (Andrews 2020). Each of the mechanisms can explain substructure formation fairly well, and it is not yet known which are major/minor or rare/common. It could be even dependent on system's properties such as disk mass, stellar mass, and accretion rates.

Given that the protostellar phase is a substructure-forming stage, the upper limit of the formation timescale can be obtained through observations towards Class 0/I sources. It sets a strong constraint for the formation mechanisms and can be a hint to understand the origins of substructures in protostellar disks as well as in protoplanetary disks.

2.3. *Spectral index, optical thickness, grain growth*

Dust continuum emission can be optically thick for the protostellar disks even at millimeter/submillimeter wavelengths. This is fairly problematic when it comes to mass estimation. An optically-thin assumption is often adopted for mass estimation, but only lower limits of mass are derivable for optically-thick sources. True disk mass is a key quantity that characterizes the physical structure of dust disks and gives information on the formation mechanisms of, if present, substructures For instance, spiral arms are a natural consequence of gravitational

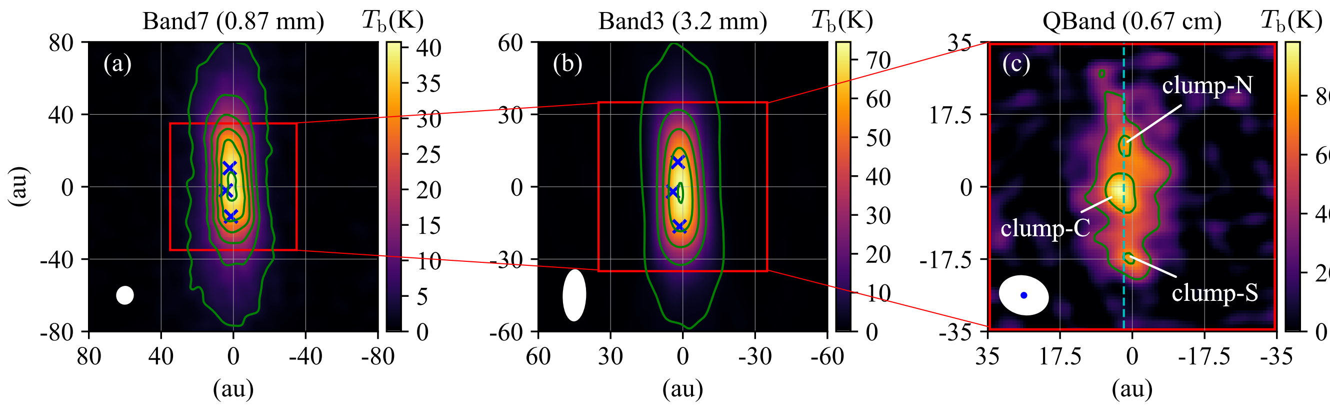

Fig. 1. Continuum images at (a) 0.87 mm (ALMA Band 7), (b) 3.2 mm (ALMA Band 3), and (c) 0.67 cm (JVLA Q Band) wavelenghts observed toward the inner disk around the Class 0/I protostar in L1527 IRS (Nakatani et al. 2020). The color maps show the brightness temperatures T_b, and the green solid lines are contours for T_b. In the ALMA Band 7 and Band 3 images, the first contour starts at 10σ, and the intervals are 23σ and 65σ, respectively; in the JVLA image, the first contour is at 3.5σ, and the interval is 3σ. The corresponding beam sizes are shown by the white ellipses at the bottom left of each panel. Within the white ellipse the in Q band image, we also show a blue–filled beam with a size of 10 mas $\times$ 10 mas for a reference angular resolution achievable by ngVLA. There are three vertically aligned clumps in the Q band image, indicative of substructures around the protostar. The clump locations are marked with the crosses in the ALMA images.

instability, and the degree of unstableness can be quantified by the Toomre Q parameter (Toomre 1964) is calculable only after disk mass is given. Dust emission can be optically thin at radio wavelengths and thus is beneficial to avoid the problem. At radio wavelengths, free-free emission can significantly contaminate dust thermal emission. A special care may be needed in such cases.

The observed spectral indices are $\alpha \approx$ 2–3 for the most VANDAM targets and gives a fit spectral index of ≈ 2.2, being consistent with optically thick to optically thin emission. Figure 2 shows a sliced α map at the vertical cyan dashed line in the right panel of Figure 1, which corresponds to the midplane of the Class 0/I disk (L1527 IRS). The spectral index α of ALMA Bands 7 and 3 data (green line) is below 2 for $\lesssim 30$ au, and that of the ALMA Band 3 and JVLA Q band data (blue line) is ~ 2 for $\lesssim 20$ au. Note that the low $\alpha(<2)$ is evident from the higher brightness temperature of the Band 3 image than that of the Band 7 image in Figure 1. These results are again consistent with optically thick dust emission at the millimeter/submillimeter wavelengths. This is also supported by a high optical depth at 7 mm derived with a model temperature distribution (Tobin et al. 2013). The anomalously low $\alpha(<2)$ can be explained by (1) hot dust layers obscured by forefront dust (Li et al. 2017; Galván-Madrid et al. 2018) and/or (2) frequency variation of dust albedo (Liu 2019; Zhu et al. 2019). Measurement of the maximum grain size is needed to understand the specific cause. Radio observations are of great importance in this sense as well. Overall, observations have demonstrated that dust continuum emission is likely optically thick at the millimeter/submillimeter wavelengths for protostellar disks. It hinders to extract fundamental information on the physical structure of protostellar systems.

In low-resolution observations, grown and small dust may often appear spatially mixed on the images. On the other hand, higher-resolution observations can resolve the vertical segregation of small and grown dust for edge-on sources. Spatial resolutions of $\lesssim 10$ mas may allow a direct imaging of sub-au-

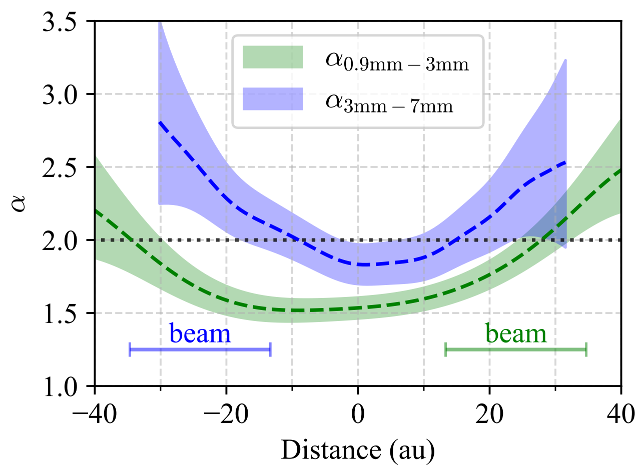

Fig. 2. Spectral index α along the vertical cyan dashed line in the right panel of Figure 1. The blue and green dashed lines are α between Bands 7 and 3, and between Band 7 and Q Band, respectively. The blue- and green-shaded regions indicate 1σ errors. The sliced beam sizes are shown at the bottom with the corresponding colors. The black dotted line is at $\alpha = 2$ and is for a reference. The spectral indices are derived using the data with $> 3\sigma$ detection at ALMA Bands 7 and 3, and JVLA Q Band (cf. Figure 1).

scale differences in the scale heights of mm- and cm-sized dust at ~ 10 au, assuming a reasonable strength of turbulent diffusion (Hasegawa et al. 2017). This would bring a quite new picture regarding grain growth and turbulence in circumstellar disks at the levels ALMA or JVLA has never reached. Hence, high angular resolution ($\ll 0\farcs1$) radio observations provides a unique tool not only to resolve substructures but also to constrain the true physical properties of circumstellar disks (e.g., mass, grain growth, turbulence, etc).

3. ngVLA Capabilities

We have raised anticipated requirements for observations towards protostellar disks especially aiming at characterization of substructures. The requirements are summarized as follows. Since Class 0/I disks are embedded in a large-scale envelope, dust thermal emission can be optically thick even at millimeter/submillimeter wavelengths. In particular, substructures are often found to be optically thick at frequencies of $\gtrsim 200\,\mathrm{GHz}$. Lower-frequency observations are optimal for investigation of Class 0/I sources to avoid the potential problems. Radio frequencies of $\gtrsim 30\,\mathrm{GHz}$, at which dust continuum emission is dominant and can get relatively optically thin, should be of particular use.

The mean radius of protostellar disks is expectedly small (~ 30–$40\,\mathrm{au}$), and the typical length scale of substructures may be much smaller; supposedly, ~ 10–$20\,\mathrm{au}$ ($< 0\farcs1$). The detected substructures are often unresolved even with the longest baseline of the currently available facilities. Higher angular resolutions ($\ll 0\farcs1$) is necessary to fully resolve substructures and to understand the detailed properties. Such very high angular resolution will also permit constraining proper motions of existing substructures; it provides a new way to look at the unidentified properties, like the geometry of the L1527's substructure, and may be interested in the case studies for vortices in general.

In these above senses, high-resolution ($< 0\farcs1$) radio observations are essential to detect/investigate substructures in protostellar disks. Large sample surveys would be required in order to conduct the investigation in a statistical manner. Only such observations make it possible to understand physical properties of protostellar disks, the degree of grain growth, and the origins of substructures. All of them are crucial information for updates to the classical planet formation scenario.

To this end, observations with ngVLA is ideal. It covers the frequency range where optically thin dust emission might dominate (30–$100\,\mathrm{GHz}$), and has sufficiently high angular resolutions (0.1–$1\,\mathrm{mas}$ at the highest). The mass sensitivity is also sufficient so that one can estimate disk mass and substructure's mass. ALMA, JVLA, or Square Kilometer Arrays (SKA) cannot meet the requirements for optical thickness and/or angular resolution. Only ngVLA provides capabilities of investigating substructures in Class 0/I sources.

4. Summary & Conclusions

While the classical planet formation scenario explains planet formation takes place in the protoplanetary phase, recent observations have brought many evidences that may suggest early planet formation in the protostellar phase. Recent discovery of substructures in Class 0/I sources is one example. Since they are thought to have a direct link to grain growth and thus planet/planetesimal formation, investigating the physical properties is an important subject in the field.

Observations towards protostellar disks and their substructures have obstacles due to the expected optical thickness of the sources and the required very high angular resolutions. ALMA, JVLA, or SKA are likely not capable of investigating the physical properties, such as disk mass, disk size, substructure's mass, substructure's geometry and grain growth. On the other hand, such investigation is only feasible with ngVLA; the frequency coverage, angular resolution, and sensitivity are advantageous not only for detectability of substructures in protostellar disks but also to characterize the structures and to understand their origins. These informations are clearly necessary for other observational/theoretical studies in the field of the stellar system formation. Observing protostellar disks *with ngVLA* is thus a essential piece to construct a next-generation planet formation scenario.

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