Ring Formation by Coagulation of Dust Aggregates in the Early Phase of Disk Evolution around a Protostar

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Abstract

Ring structures are observed through (sub)millimeter dust continuum emission in various circumstellar disks from the early stages of class 0 and I to the late stage of class II young stellar objects (YSOs). In this paper, we study one of the possible scenarios for such ring formation, which is the coagulation of dust aggregates in the early stage. The dust grains grow in an inside-out manner because the growth timescale is roughly proportional to the orbital period. The boundary of the dust evolution can be regarded as the growth front, where the growth time is comparable to the disk age. Using radiative transfer calculations based on the dust coagulation model, we find that the growth front can be observed as a ring structure because the dust surface density changes sharply at this position. Furthermore, we confirm that the observed ring positions in YSOs with an age of \( \lesssim 1 \) Myr are consistent with the growth front. The growth front could be important in creating the ring structure in particular for the early stage of disk evolution, such as class 0 and I sources.

Unified Astronomy Thesaurus concepts: Protoplanetary disks (1300); Dust continuum emission (412); Interstellar medium (847); Protostars (1302); Young stellar objects (1834); Circumstellar disks (235); Star formation (1569); Planetary system formation (1257)

1. Introduction

A Keplerian disk that forms around a protostar plays an essential role in planet formation. Recent high spatial resolution observations of dust emission with interferometers uncover a variety of pictures of disk structures from the early stage of disk formation (e.g., Sheehan & Eisner 2017, 2018; Takakuwa et al. 2017; Garufi et al. 2020; Sai et al. 2020; Tobin et al. 2020) to the late stage of protoplanetary disks (e.g., Casassus et al. 2013; van der Marel et al. 2013; ALMA Partnership et al. 2015; Isella et al. 2016; Andrews et al. 2018; Fedele et al. 2018; Tsukagoshi et al. 2019). In particular, dust ring structures have been observed in many protoplanetary disks. For example, the first ALMA Long Baseline Campaign observations show prominent ring and gap structures of the HL Tau disk at 30 mas resolution (ALMA Partnership et al. 2015). The Disk Substructures at High Angular Resolution Project (DSHARP) in the ALMA Cycle 4 Large program (Andrews et al. 2018) has also shown that disks have gap/ring structures in a sample of large and bright disks (Huang et al. 2018).

The observed ring structures are believed to be caused by changes in density or dust opacity over the disk. The formation mechanism of such ring structures remains unknown even though various mechanisms to create dust rings have been proposed, such as the density gap formed by the gravitational interaction between the disk and unseen giant planets (e.g., Goldreich & Tremaine 1980; Nelson et al. 2000; Paardekooper & Mellema 2004; Zhu et al. 2012; Kanagawa et al. 2015; Zhang et al. 2018), magnetorotational instability (MRI; Flock et al. 2015), magnetohydrodynamics (MHD) wind (Riols & Lesur 2019; Suriano et al. 2019), both snow line and non-MHD effects (Hu et al. 2019), secular gravitational instability (Takahashi & Inutsuka 2014), snow lines of molecules or dust sintering (Zhang et al. 2015; Okuzumi et al. 2016), and so on. These studies are mainly motivated by observations of protoplanetary disks around class II sources.

Interestingly, dust ring structures are observed not only in class II protoplanetary disks, but also even in earlier stages of disk formation around class 0 and class I objects (e.g., Sheehan & Eisner 2017, 2018; Sheehan et al. 2020; Nakatani et al. 2020). The formation of ring structures in growing young disks requires a much shorter time, and its mechanisms could be constrained more. Such approach was started after the discovery of infant disks around young embedded protostars (Tobin et al. 2012; Ohashi et al. 2014; Yen et al. 2014). For example, gap formation by an unseen planet(s) makes it difficult to form planets at such an early stage. MHD wind has been proposed to create a ring structure in such young disks. Takahashi & Muto (2018) showed that the MHD wind creates a hole structure in young disks, through which disk material inside the MHD wind is lost.

In this paper, we investigate an alternative scenario for the ring-formation mechanism in the early phase of disk evolution. We focus on the evolutionary process of dust aggregates by coagulation because grain growth is important in disks. The model of evolution through dust coagulation has been studied through various mechanisms to create dust rings have been proposed, such as the density gap formed by the gravitational interaction between the disk and unseen giant planets (e.g., Goldreich & Tremaine 1980; Nelson et al. 2000; Paardekooper & Mellema 2004; Zhu et al. 2012; Kanagawa et al. 2015; Zhang et al. 2018), magnetorotational instability (MRI; Flock et al. 2015), magnetohydrodynamics (MHD) wind (Riols & Lesur 2019; Suriano et al. 2019), both snow line and non-MHD effects (Hu et al. 2019), secular gravitational instability (Takahashi & Inutsuka 2014), snow lines of molecules or dust sintering (Zhang et al. 2015; Okuzumi et al. 2016), and so on. These studies are mainly motivated by observations of protoplanetary disks around class II sources.
Okuzumi et al. (2012), and others in order to investigate the formation of planetesimals or planets, but its connection to the ring structures has not been explored. By using this dust model, we discuss whether dust evolution by coagulation can be observed as a ring structure during grain growth.

2. A Picture of Keplerian Disk Formation with Dust Evolution

Before investigating dust growth by coagulation in a Keplerian disk, we discuss the dust evolution process from the infalling envelope to the disk region.

Stars are formed via gravitational collapse in dense cores, and protoplanetary disks are formed as by-products of star formation (e.g., Williams & Cieza 2011). A Keplerian-rotation disk is formed around a protostar with a slowly rotating dense core. The Keplerian disk expands through the accretion of the infalling envelope.

Hirashita & Omukai (2009) calculated the dust coagulation in collapsing prestellar cores and showed that the dust grain does not grow in the envelope because the density of $10^5$–$10^7$ cm$^{-3}$ is not high enough to grow dust grains. Ormel et al. (2009) also investigated the coagulation in dense cores and suggested that the freefall time of collapsing cores is not long enough for grain growth to proceed during the gravitational collapse. Therefore, we assume dust coagulation in the Keplerian disk region rather than in the infalling envelope. The idea of ring formation by dust coagulation works as long as there is a Keplerian disk, even though the disk is embedded in the envelope, because infalling materials will accrete to the outer edge of the disk, while ring formation is considered to happen inside the disk.

The Keplerian disk becomes larger as it accretes material from the infalling envelope. Disk growth may need to be taken into account. However, this study assumes that the disk is already formed before dust coagulation occurs. This is a case where the timescale of disk evolution is faster than that of dust coagulation in the disk. We note that further studies are needed to investigate whether disk growth is earlier than dust growth.

3. Theoretical Model of Dust Growth

3.1. Disk Model

In this subsection, we describe a dust coagulation model. The results of the evolution of the surface density and grain size are shown in Section 3.2.

A simple method for calculating dust surface density and particle size distribution is adopted from Sato et al. (2016), who investigated the water composition of planets due to ice pebble accretion across the snow line. We consider two factors of dust evolution: (1) grain growth via coagulation and (2) radial drift of dust grains.

The initial gas surface density ($\Sigma_g$) is set to be

$$\Sigma_g = 1.7 \times 10^3 \left(\frac{r}{1 \text{ au}}\right)^{-3/2} \text{ g cm}^{-2},$$

based on the minimum mass solar nebula (MMSN) model of Hayashi (1981). We ignore the jump of the surface density due to the snow line because the position of the snow line is at $\sim$3 au, which is smaller than both the area to be investigated and the observed ring positions ($\sim$10–100 au). The initial dust surface density ($\Sigma_d$) is set to be 1% of the dust surface density.

The dust temperature of the disk is determined by assuming a thermal equilibrium as follows:

$$T = 280 \left(\frac{r}{1 \text{ au}}\right)^{-1/2} \left(\frac{L}{L_\odot}\right)^{1/4} \text{ K}.$$  \hspace{1cm} (2)

The initial size of the dust particle is uniformly set to 0.1 $\mu$m. The mass distribution of dust particles is assumed to have a single peak in mass $m_p(r)$ at each radial distance $r$. Then, assuming that the dust surface density $\Sigma_d$ at each orbit $r$ is dominated by particles with mass $m_p$, we follow how the peaks of the dust surface density $\Sigma_d$ and mass $m_p$ change with coagulation and radial drift. Note that we assume that the dust aggregates are so sticky that no fragmentation or bouncing occurs upon collision. According to Sato et al. (2016), the equations of the evolution of $\Sigma_d$ and $m_p$ are given by

$$\frac{\partial \Sigma_d}{\partial t} + \frac{1}{r} \frac{\partial}{\partial r} (rv_\Sigma \Sigma_d) = 0,$$  \hspace{1cm} (3)

$$\frac{\partial m_p}{\partial t} + \frac{v_t}{r} \frac{\partial m_p}{\partial r} = \frac{2\sqrt{\pi}}{a^2} \Delta v_{pp} \Sigma_d,$$  \hspace{1cm} (4)

where $a = (3m_p/4\pi \rho_{int}^{1/3})$ is the particle radius, $v_t$ is the radial drift velocity of the particles, $\Delta v_{pp}$ is the relative velocity of the particles, $\rho_{int}$ is the internal density of dust grains, and $h_d$ is the dust scale height. The internal density of dust grains is fixed to be a typical value of $\rho_{int} = 1.4$ g cm$^{-3}$ for simplicity, while low-density dust grains, such as fluffy dust grains, decrease the internal density to $\rho_{int} \sim 10^{-5}$–$10^{-9}$ g cm$^{-3}$ (Okuzumi et al. 2012). The other $v_t$, $\Delta v_{pp}$, and $h_d$ are described as follows.

The radial drift velocity of particles is given by Adachi et al. (1976) and Weidenschilling (1977):

$$v_t = -\frac{2St}{1 + St^2} \rho_{int} K,$$  \hspace{1cm} (5)

where

$$St = \frac{\pi \rho_{int} a}{2 \Sigma_g}$$  \hspace{1cm} (6)

is the Stokes number and

$$\eta = \frac{1}{2} \left(\frac{c_s}{v_K}\right)^2 \frac{d \ln (c_s \rho_g)}{d \ln r}$$  \hspace{1cm} (7)

is a dimensionless quantity characterizing the pressure gradient of the disk gas, $c_s$ is the sound speed, and $v_K = r \Omega_K$ is the Kepler velocity, where $\Omega_K = \sqrt{GM_*/r^3} = 2.0 \times 10^{-7}$ (r/1 au)$^{-3/2}$ ($M_*/M_\odot$)$^{1/2}$s$^{-1}$ is the Keplerian frequency with $G$, $M_*$ being the gravitational constant and central stellar mass, respectively. In our disk model, $\eta v_K = 33$ms$^{-1}$ is derived.

The particle collision velocity $\Delta v_{pp}$ is given by

$$\Delta v_{pp} = \sqrt{(\Delta v_H)^2 + (\Delta v_t)^2 + (\Delta v_o)^2 + (\Delta v_z)^2 + (\Delta v_i)^2},$$  \hspace{1cm} (8)

where $\Delta v_H$, $\Delta v_t$, $\Delta v_o$, $\Delta v_z$, and $\Delta v_i$ are the relative velocities induced by Brownian motion, radial drift, azimuthal drift, vertical settling, and turbulence, respectively. Detailed equations of each component are shown in the Appendix.

The dust scale height is determined by a balance between vertical settling and turbulent diffusion and is written as (e.g., Dubrulle et al. 1995; Schräpler & Henning 2004;
point out that the position of the growth front (the pebble production line) is independent of the dust structures, disk mass, temperature, or the turbulence strength, as explained in the following discussion.

As demonstrated by many previous studies (e.g., Takeuchi & Lin 2005; Garaud 2007; Brauer et al. 2008; Birnstiel et al. 2010, 2012; Okuzumi et al. 2012), the dust evolution can be estimated from the growth timescale. The growth rate of the aggregate mass \( m \) at the midplane is given (Tanaka et al. 2005) by

\[
\frac{dm}{dt} = \rho_d \sigma_{\text{coll}} \Delta v = \frac{\Sigma_d \sigma_{\text{coll}} \Delta v}{2 \pi h_d},
\]

where \( \rho_d = \Sigma_d / (2 \pi h_d) \) is the spatial dust density at the midplane, and \( \sigma_{\text{coll}} \) is the collisional cross section of two dust particles. Then, Equation (10) can be rewritten in terms of the growth timescale as

\[
t_{\text{grow}} = \left( \frac{m}{\rho_d \sigma_{\text{coll}} \Delta v} \right) = \frac{4 \sqrt{2 \pi} h_d \rho_{\text{inst}} a^3}{\Sigma_d \Delta v \Sigma_d},
\]

where \( m = (4 \pi / 3) \rho_{\text{inst}} a^3 \) and \( \sigma_{\text{coll}} = \pi a^2 \).

Here, we focus on the millimeter-size dust grains because these grains are sensitive to millimeter-wave emission. For millimeter-size dust grains, \( h_d \sim \sqrt{\alpha_{\text{inst}}/S_t h_e} \) and \( \Delta v \sim \Delta v_t \sim \sqrt{\alpha_{\text{inst}} S_t c_i} \) (Brauer et al. 2008). Then, we obtain

\[
t_{\text{grow}} \sim \left( \frac{\Sigma_d}{\Sigma_d} \right) \frac{1}{\Omega_K}.
\]

Equation (12) indicates that dust evolution commences from inside out because the growth timescale is roughly proportional to the orbital period. Furthermore, the growth timescale does not depend on the other parameters such as the internal density of dust grains (\( \rho_{\text{inst}} \)) and turbulence (\( \alpha_{\text{inst}} \)) except for the dust to gas mass ratio (\( \Sigma_d / \Sigma_g \)). Therefore, the dust growth time is independent of the fluffiness of dust, the disk mass, temperature, or the strength of the disk turbulence, while it will become shorter by increasing the dust mass ratio. Outside of the growth front, the dust particles still remain in their initial state because they have not evolved yet, while the dust grains grow inside of the growth front by radial drifting. As a result, the dust surface density is maximized at the growth front (see Figure 1). Therefore, a ring structure is expected to be observed at the growth front. However, it should be noted that the ring structure of the growth front has not been seen so far even though its existence is well known.

### 3.3. Dependence on the Initial Conditions

We investigate the dependence of the growth front on the initial conditions. Even though the MMSN model is applied to the disk evolution in the previous subsection, protostellar disks in the class 0/I stage may have higher accretion rates and higher surface densities. Therefore, we calculate the disk evolution by changing the radial drift velocity and surface densities of gas and dust in the initial conditions.

Figure 2 shows the results of the case where the gas and dust surface densities are 10 times higher than the MMSN model. The dust to gas mass ratio remains at 1%. Furthermore, to investigate the dependence of the radial drift velocity (\( v_t \)) on the growth front, we use a 10 times higher the value of \( \eta \) given in Equation (7). Thus, \( \eta_{\text{K}} = 330 \) m s\(^{-1}\) is used. Figure 3 shows the disk evolution with the initial grain size of 1 \( \mu m \), which is
the case where the initial grain size is 10 times larger than the previous MMSN model. By comparing Figures 1, 2, and 3, we find that the growth front and radial profiles of dust, gas, and grain size are hardly changed with changing initial conditions. The growth front appears independently of the initial surface densities, radial velocity, and grain size. This is consistent with the result that the growth timescale depends only on the dust to gas mass ratio \( \gamma_{d/g} \) and the orbital period \( \Omega_K \) shown in Equation (12). Therefore, the disk evolution and growth front would be robust once the Kepler disk is formed even if surrounding materials accrete onto the disk from the envelope.

3.4. Dust Ring Structure at the Growth Front by Radiative Transfer Calculations

In this subsection, we demonstrate that a disk with a growth front can be observed as a ring using radiative transfer calculations with RADMC-3D\(^7\) (Dullemond et al. 2012). The physical structure of the disk is shown in the previous subsection and Figure 1. The calculation setup for the radiative transfer is described as follows.

We analyze the disk with two different observing wavelengths to investigate the dependence of the growth front on the observing wavelength. The observing wavelengths are set to \( \lambda = 870 \ \mu m \) and 7 mm, corresponding to ALMA Band 7 and VLA \( Q \)-band observations, respectively. The distance is assumed to be 100 pc. The intensity is calculated using the radiative transfer equation with the given dust surface density, temperature, and dust absorption/scattering opacity.

The dust opacity is calculated using Mie theory. We calculate the dust evolution under the assumption of a power-law size distribution with an exponent of \( q = 3.5 \) (Dohnanyi 1969; Tanaka et al. 1996). Although the index \( q \) is modified due to the mass dependence of velocity (Kobayashi & Tanaka 2010), we put \( q = 3.5 \) for simplicity. Note that collisional sticking effectively occurs for \( D \lesssim v \approx 80 \text{ m s}^{-1} \) (Wada et al. 2013), and this condition is satisfied in the entire disk for our calculations.

The dust composition was assumed to be a mixture of silicate (50%) and water ice (50%; Pollack et al. 1994). We used the refractive index of astronomical silicate (Weingartner & Draine 2001) and water ice (Warren 1984) and calculated the absorption and scattering opacity based on effective medium theory using the Maxwell–Garnett rule (e.g., Bohren & Huffman 1983; Miyake & Nakagawa 1993). Figure 4 shows absorption and scattering opacity as a function of dust grain size.

The radiative transfer calculation is performed without changing the dust scale height for each dust size. If the disk is face on, the variations of the dust scale height will be less affected. Here, we assume that the dust scale height is an order of magnitude thinner than the gas scale height.

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\(^7\) RADMC-3D is an open code for radiative transfer calculations developed by Cornelis Dullemond. The code is available online at https://www.ita.uni-heidelberg.de/~dullemond/software/radmc-3d/.
spectral index takes the peak value of $\alpha_{0.87\text{mm}-7\text{mm}} \sim 4.1$–4.4 at the growth front because the growth front has millimeter-size dust grains that efficiently emit thermal radiation at the 860 $\mu$m observing wavelengths. According to Figure 3 of Ricci et al. (2010), dust grains with a size of $<100$ $\mu$m show a spectral index of $\beta \sim 1.7$, those with a size of $\sim 0.1$–1 mm show $\beta \sim 2$–3, and those with a size of $>1$ mm show $\beta < 1.5$. Note that the observed (sub)millimeter spectral index ($\alpha$) is related to $\beta$ by $\alpha = \beta + 2$ in the Rayleigh–Jeans limit. Thus, these $\alpha$ values are consistent with the grain sizes of our dust model. Therefore, the spectral index is a possible way of identifying the growth front.

It should be noted that the estimates of grain sizes from the spectral index depend on the dust model such as dust chemical composition, power law of dust size distribution, porosity, and so on. Even though the absolute value of the spectral index, $\alpha$, changes with the dust model, the behavior of the spectral index is robust.

3.6. Growth Front Location

We formulate the ring location. Equation (12) indicates the timescale of the dust evolution, which is a function of the Keplerian frequency $\Omega_K$. In other words, if the timescale ($t_{\text{grow}}$) is set to the disk age ($t_{\text{age}}$), we can derive the critical radius ($R_c$) the growth front reaches, because $\Omega_K \propto r^{-3/2}$. The critical radius can be estimated by transforming Equation (12) into a function of $r$. Thus, Equation (12) yields

$$R_c = A \left( \frac{M_*}{M_\odot} \right)^{1/3} \left( \frac{\zeta_d}{0.01} \right)^{2/3} \left( \frac{d_{\text{disk}}}{1 \text{ yr}} \right)^{2/3} \text{ au},$$

(14)

where $A$ is the transformation coefficient and $\zeta_d = \Sigma_d/\Sigma_\text{g}$. The coefficient $A$ can be derived by fitting the various ring positions over time to Equation (14). Therefore, we perform the radiative transfer calculations for the model at $t = 6.4 \times 10^3 \text{ yr}$, $1.3 \times 10^4 \text{ yr}$, $2.6 \times 10^4 \text{ yr}$, $5.2 \times 10^4 \text{ yr}$, and $1.0 \times 10^5 \text{ yr}$ by assuming $\lambda = 870 \mu$m, $M_* = 1 M_\odot$, and $\zeta_d = 0.01$. Then, we identify the ring position. Figure 7 shows the time evolution of the ring position. The error of the ring position indicates the FWHM derived by direct measurements of the synthetic images. By fitting the ring positions to Equation (14), $A$ is derived to be 0.026.

4. Observational Study of the Growth Front

In the previous section, we showed that the dust coagulation model is one possible scenario for the formation of the dust ring. The dust ring position (growth front) moves outward over time because the growth timescale is roughly proportional to the orbital period. Here, we discuss the growth front and observed dust ring positions.

4.1. Comparison with Observations

In this subsection, we compare the growth front position with observed ring positions. Many dust ring structures have been identified with ALMA high spatial resolution observations even though the origin of such rings is still under debate.

We use the results of the DSHARP project (Andrews et al. 2018) as Huang et al. (2018) listed the positions of the dust rings of the 18 disks in the DSHARP sample. In addition, our sample includes HL Tau (class II) and three class 0/I objects
These objects are reported to have possible ring structures. A total of 23 disks having ring structures are investigated. Table 1 lists the source name, stellar mass ($\sum M$), age ($t_{\text{age}}$), and growth front radius ($R_c$). The location of the growth front is derived by using Equation (14) assuming $t_{\text{disk}} = t_{\text{age}}$ and $A = 0.026$. Table 1 also lists the observed ring positions ($R_p$). From these samples, we show the ring position ($R_p$) against stellar age in Figure 8. Because some disks have multiple rings, the symbols in the figure are changed according to the order of the rings. The rings of class 0/I objects are shown in red and those of class II objects are shown as open symbols. The errors of the stellar age are estimated by Andrews et al. (2018) in the DSHARP sample, and we use the average value of a factor of 2 error in all sources.

As shown in Figure 8, we find no correlation between stellar age and ring location. The ring location ranges from $\sim$10 to $\sim$100 au independent of stellar age. Van der Marel et al. (2019) also find no evidence of a snow line nor resonances of planets by investigating the gap/ring radii of 16 disks with stellar age and luminosity. Therefore, the origin of these dust ring (and gap) structures so far remains unclear.

To investigate the origin of the ring structure through the growth front, we plot the ring location ($R_p$) normalized by the growth front ($R_c$) with respect to the stellar/disk age in Figure 9. This figure shows that there are some rings with a
Figure 7. The ring positions of our model against time. The red line indicates the fitting to Equation (14) to derive the transformation coefficient $\alpha$.

ratio ($R_{\circ}/R_e$) of almost unity within the disk age of less than 1 Myr, suggesting that the one of the ring positions in these young disks corresponds to the growth front. Therefore, the growth front can explain the ring structure in particular for the early stage of disk evolution such as in class 0 and I sources. Note that the error of $R_e$ is calculated from the error of the stellar age because the stellar age has the largest uncertainty.

In contrast, the ratio $R_{\circ}/R_e$ decreases after 1 Myr, indicating that the growth front extends much larger than the observed ring positions. The growth front is even larger than the disk radii in several protoplanetary disks. These observed ring structures cannot be explained by the growth front. Thus, we suggest that the origin of the rings would be different from the growth front in the protoplanetary disks around class II objects after 1 Myr.

4.2. A Case Study of the Growth Front: L1527

In the previous subsection, we find that the growth front shows the ring structure and is consistent with observed ring positions, in particular for the disks around class 0 and I sources. Here, we investigate dust coagulation in more detail in an ideal disk where an observed dust ring is consistent with a growth front. We expect that dust size would be different inside and outside the growth front. Inside the growth front, dust grains are expected to be larger. In contrast, outside the growth front, dust growth has not yet proceeded, and dust size is expected to be small. Therefore, the spectral indices have different values across the growth front as shown in Figure 6.

We consider the disk in the class 0/I source L1527 to be an ideal target to investigate dust coagulation because the ring position ($R_{\circ} = 15$ au) is consistent with the growth front ($R_e = 22^{+15}_{-3}$ au) within the error and also because observations over a wide range of wavelengths were performed toward this source. L1527 is well studied by many observations with ALMA and VLA, and has been revealed to be forming a Keplerian disk with a radius of 80 au (e.g., Tobin et al. 2012; Ohashi et al. 2014; Sakai et al. 2014, 2019; Aso et al. 2017). Nakatani et al. (2020) found substructures within the Keplerian disk by using VLA 7 mm dust continuum observations and interpreted this structure as a dust ring even though the disk is viewed almost edge on.

We show the L1527 images of ALMA Band 3 and VLA $Q$-Band continuum data in Figure 10. The wavelengths of ALMA Band 3 and VLA $Q$ Band are 3 mm and 7 mm, respectively. The spectral index $\alpha_{3\text{mm}-7\text{mm}}$ map is also shown in Figure 10 and is discussed later in this section. The morphology of these continuum emission is described in detail in Nakatani et al. (2020). Here, we point out that the VLA $Q$-Band image indicates equally spaced clumps along the north–south direction at a distance of 15 au from the central protostar, which is interpreted as a ring structure in the edge-on disk. The ALMA Band 3 image shows no sign of the substructure, which would be due to the large beam size of the ALMA Band 3 observations. The optical depth may also affect the continuum image if the emission is optically thick.

To compare the L1527 disk with the growth front, we show the dust coagulation model images of the 7 mm continuum emission and spectral index maps of $\alpha_{0.87\text{mm}-7\text{mm}}$ and $\alpha_{3\text{mm}-7\text{mm}}$ at $t = 1.3 \times 10^4$ yr from an edge-on view in Figure 11. The MMSN model with a one solar mass protostar is applied for this simulation as the fiducial model. Note that the face-on view is already shown in Figure 5. The model images are smoothed with a VLA beam size of $0.086^\prime \times 0.067^\prime$. We find that the 7 mm continuum image has double clumps at the growth front radius similar to the observations because the ring structure has the longest line of sight at the edges. Therefore, we confirm that the observed double clumps are explained by the ring structure. The substructure is found more clearly in the edge-on disk than the face-on disk with 7 mm continuum emission because the contrast of the surface density is enhanced in the edge-on view. We note that the intensity and spectral index values of the model are quite different from the observations because we use the MMSN model in this study. The comparison of models and observations based on intensity and spectral index is only a qualitative discussion.

The spectral index maps, $\alpha_{0.87\text{mm}-7\text{mm}}$ and $\alpha_{3\text{mm}-7\text{mm}}$, of our model are derived using intensities between 870 $\mu$m and 7 mm and wavelengths between 3 mm and 7 mm. We find that the edge-on disk shows a different spectral index pattern from the face-on disk at the growth front. In the face-on disk, the spectral index peaks at the growth front with $\alpha_{0.87\text{mm}-7\text{mm}} \sim 4.2$ as shown in Figure 6, whereas in the edge-on disk, the spectral index decreases at the growth front with $\alpha_{0.87\text{mm}-7\text{mm}} \sim 2.8$ and $\alpha_{3\text{mm}-7\text{mm}} \sim 3.0$ as shown in Figure 11. The difference between the edge-on and face-on disk models is the optical depth. The optical depth at the growth front in the edge-on disk becomes higher than that in the face-on disk. The optically thick emission follows blackbody radiation, which means the spectral index $\alpha = 2$. By taking into account the beam dilution of the VLA observations, the spectral index becomes larger than 2 but lower than that of the optically thin case. The self-scattering of dust grains (Kataoka et al. 2015) may also affect the intensity of the dust thermal emission and spectral index at millimeter wavelengths (e.g., Soon et al. 2017; Ueda et al. 2020). Liu (2019) and Zhu et al. (2019) showed that the spectral index decreases by scattering if emission is optically thick because the scattering of (sub)millimeter-size dust grains makes the (sub) millimeter thermal emission fainter. As a result, the spectral index becomes flatter or steeper than the case without the scattering effect. Therefore, the spectral index of the growth front can be changed by the optical depth and effect of the scattering. However, Figure 11 shows that the increase in the spectral index from inside to outside the growth front still remains because dust grains are large/small enough to not be affected by the scattering effect.
Table 1
Data Sample

| Name   | Stellar Mass \((M_\odot)\) | Age \(t_{\text{age}}\) (Myr) | Growth Front \(R_\text{p}\) (au) | Class | Observed Ring Position \(R_\text{p}\) (au) |
|--------|-----------------------------|-----------------------------|---------------------------------|-------|-------------------------------------------|
| L1527  | 0.5* 0.037*                  |                             |                                 | 22    | 0/1 15 (a)                                |
| WL 17  | 0.3 0.1                      | 38                          | 0/1                             | 17    | (b)                                        |
| IRS 63 | 0.8 0.13                     | 62                          | 0/1                             | 27    | (c)                                        |
| GY 91  | 0.3 0.5                      | 100                         | 0/1                             | 25    | (d) 55 (d) 82 (d)                         |
| Elias 24 | 0.8 0.2                     | 81                          | II                              | 77    | (e) 123 (e)                               |
| WSB 6  | 0.7 0.3                      | 110                         | II                              | 88    | (e)                                        |
| IM Lup | 0.9 0.5                      | 160                         | II                              | 134   | (e)                                        |
| RU Lup | 0.6 0.5                      | 140                         | II                              | 17    | (e) 25 (e) 34 (e) 50 (e)                 |
| HL Tau | 0.5 0.5                      | 130                         | II                              | 21    | (f) 40 (f) 49 (f) 58 (f) 72 (f) 85 (f) 102 (f) |
| SR 4   | 0.7 0.8                      | 200                         | II                              | 18    | (e)                                        |
| Elias 27 | 0.5 0.8                    | 180                         | II                              | 86    | (e)                                        |
| AS 209 | 0.8 1                        | 240                         | II                              | 14    | (e) 28 (e) 39 (e) 74 (e) 97 (e) 120 (e) 141 (e) |
| Sz 114 | 0.2 1                        | 140                         | II                              | 45    | (e)                                        |
| DoAr 33 | 1.1 1.6                     | 360                         | II                              | 17    | (e)                                        |
| DoAr 25 | 1 2                        | 410                         | II                              | 86    |
|        |                              |                             |                                 | (e)   | 111 (e) 137 (e)                           |
| GW Lup | 0.5 2                        | 320                         | II                              | 85    | (e) 108 (e)                               |
| HD 143006 | 1.8 4                    | 790                         | II                              | 6    |
|        |                              |                             |                                 | (e)   | 41 (e) 65 (e)                             |
| Sz 129 | 0.8 4                        | 610                         | II                              | 10    | (e) 46 (e) 69 (e)                         |
| MY Lup | 1.2 10                       | 1300                        | II                              | 20    | (e)                                        |

Table 1 (Continued)

| Name   | Stellar Mass \((M_\odot)\) | Age \(t_{\text{age}}\) (Myr) | Growth Front \(R_\text{p}\) (au) | Class | Observed Ring Position \(R_\text{p}\) (au) |
|--------|-----------------------------|-----------------------------|---------------------------------|-------|-------------------------------------------|
| HD 163296 | 2 12.6                    | 1800                        | II                              | 14    | (e) 67 (e) 100 (e) 155 (e)               |
| HD 142666 | 1.6 12.6                  | 1600                        | II                              | 6    | (e) 20 (e) 40 (e) 58 (e)                 |

Note.
- The mass and age are estimated by Aso et al. (2017) and Takahashi et al. (2016), respectively.

References.
- (a) Nakatani et al. (2020), (b) Sheehan & Eisner (2018), (c) Segura-Cox et al. (2020), (d) Sheehan & Eisner (2017), (e) Huang et al. (2018), (f) ALMA Partnership et al. (2015).

Figure 8. The positions of the observed dust rings \(R_p\) are shown against the stellar age. Because some disks have more than one ring, the symbols in the figure are changed according to the order of the rings. Furthermore, class 0/I object rings are shown in red, and class II rings are shown as open symbols.

These models assume the same scale height for different size grains. We consider that the scale height would not be affected by the current observations because none of the observations were able to resolve the scale height structure. The emission between 870 \(\mu\)m and 7 mm will be mostly from the disk midplane.

Figure 12 shows the radial profile of the observed spectral index \(\alpha_{3\text{mm}-7\text{mm}}\) overlaid with the ring position \(R_p = 15\) au as the gray dots and with the growth front \(R_p = 22\) au as the black line. The red squares indicate the spectral index along the north direction, while the blue squares indicate that along the south direction. The upper limit of the spectral index is also derived by using the 3\(\sigma\) of the VLA continuum emission.

We find that the spectral index becomes lower than 2 in the inner radius even though optically thick emission follows
blackbody radiation with the spectral index $\alpha = 2$. Therefore, the VLA $Q$-Band emission in the inner region will be affected by free–free emission from the protostar and may also be affected by the dust scattering. Even though there is contamination from the free–free emission, the spectral index $\alpha_{3\text{mm}-7\text{mm}}$ seems to increase outside the ring. This trend still remains even after extracting the free–free contamination (Nakatani et al. 2020). The increase in the spectral index along the radius indicates that the dust grains are smaller outside the radius. On the other hand, $\alpha \sim 2$ in the inner radius indicates that the dust grains have already grown and/or dust continuum emission is optically thick.

The behavior of the spectral index across the ring position is consistent with the idea of a growth front even though the absolute value of the spectral index is different from the model. Coagulation and grain growth proceed inside the growth front, resulting in a lower spectral index. On the other hand, the dust grains outside the growth front are not evolved yet. Therefore, the spectral index is higher in the outer radius than the inner radius. However, the spatial resolution is not enough to identify the sharp transition of the spectral index across the growth front.

We note that the 870 $\mu$m and 3 mm dust continuum emission would at least be optically thick (this might also be the case for 7 mm dust continuum, in particular for the clump peaks). Therefore, it is difficult to conclude that the dust grains have already grown inside the growth front because the low spectral index can also be explained by high optical depth. Further observations with high spatial resolution and longer wavelength will allow us to measure the spectral index in more detail.

### 4.3. A Caveat on Ring Formation Due to the Growth Front

Even though we show that the growth front is consistent with the observed ring location, we point out an inconsistency between our model and observations. The growth front can only explain a single dust ring even though some of the disks have multiple ring structures. Even in the class I source of GY 91, three dust rings are observed (Sheehan & Eisner 2018). As shown in Figure 9, the growth front mainly coincides with the outermost ring. Therefore, we need additional scenarios to explain the formation(s) of the entire ring. However, recent VLA observations show that substructures in protostellar disks are dominated by a single bright ring (Sheehan et al. 2020).

One way to distinguish the mechanisms of ring formation would be the spectral index $\alpha$ as shown in Figure 6. If ring structures are formed by a pressure bump due to the presence of planets, dust grains become larger in the ring positions. On the other hand, the growth front will change the dust grain size inside and outside the ring. The grain size would be larger on the inside of the ring than on the outside of the ring and at the ring position.

### 5. Discussion and Summary

The location of the growth front ($R_c$) is estimated using Equation (14). We recall that $R_c$ is independent of the dust fluffiness, disk mass, temperature, or the strength of turbulence. Therefore, the growth front could be universally observed in various protostellar disks even though we show the dust surface density of the MMSN model in this study. Even in the high accretion stage for young protostellar disks, the dust coagulation model is applicable by regarding high accretion to be the high turbulence parameter with a value of $\alpha_D$.

We roughly estimate the occurrence rate of the growth front for observations. The growth front will be difficult to observe if the disk and growth front are small. Therefore, if a disk is younger than $10^3$ yr, the growth front cannot be observed with a spatial resolution of $\sim$ a few astronomical units, such as ALMA observations. Furthermore, if a disk is more evolved than $\sim 3 \times 10^3$ yr, the growth front is beyond the disk size of 100 au and cannot be observed. Thus, the growth front can only be observable if the disk age is between $\sim 10^3$ and a few $\sim 10^4$ yr. By taking into account the lifetime of PPDs of a few Myr (e.g., Haisch et al. 2001), the occurrence rate will be $\sim$ a few percent. This may be helpful for statistical studies of survey observations in the future even though there are some uncertainties for this estimate such as disk size and lifetime. Note that this estimate is similar to that of class 0/1 sources (e.g., Evans et al. 2009). If targets are only limited to class 0/1 sources, the occurrence rate will become much higher.

By comparing with observations, we found that the ring positions in young stellar objects (YSOs) with an age of $\lesssim 1$ Myr are consistent with the growth font. Therefore, we propose that the growth front creates the ring structure in particular for the early stages of disk evolution such as class 0 and I sources. These results indicate that grain growth via coagulation occurs quickly and creates the ring structure that is observed in various disks. For disks with high accretion rates such as class 0 and I sources, it is difficult to create a situation that suppresses radial motion and has a ring. The growth front scenario is preferred to explain ring formation and the high accretion rate, simultaneously.

In contrast, the growth front extends to much larger distances than the observed ring positions and even disk radii in protoplanetary disks after 1 Myr. The observed rings in such late-stage disks would be caused by different mechanisms rather than the growth front. Because the growth front has already swept the entire disk, it may be possible to create ring/gap structures due to the presence of planets, snow lines of molecules, dust sintering, and other mechanisms in those protoplanetary disks after 1 Myr. By taking into account the
results that sufficient mass remains for planet formation in class 0/I sources but disappears in class II (e.g., Manara et al. 2018; Tobin et al. 2020), planet formation may begin after the passage of the growth front.

The existence of the growth front can be found by changing the dust size across the growth font. Analysis of the dust spectral index is an important tool for constraining the dust particle sizes in the disk. We have investigated the disk around the L1527 protostar by using the ALMA Band 3 and VLA Q-Band continuum emission as a case study.

The behavior of the spectral index $\alpha$ around the ring position is consistent with the idea of a growth front because $\alpha$ increases outside the growth front even though the absolute value is different from that in the edge-on disk model. We note that the comparison of models and observations based on intensity and spectral index is only a qualitative discussion. We suggest that the emission at least in ALMA Band 3 may be optically thick with insufficient spatial resolution, and Q-Band emission will be affected by the free–free emission from the protostar. Future observations with high spatial resolution and longer wavelengths toward various young disks will allow us to measure the spectral index in more detail.

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Facilities: ALMA, VLA.
Software: RADMC-3D (Dullemon et al. 2012).

Appendix

Equations of Relative Velocities Induced by Brownian Motion, Radial Drift, Azimuthal Drift, Vertical Settling, and Turbulence

The Brownian component is given by

\[ \Delta v_B = \sqrt{\frac{8(m_1 + m_2)k_B T}{\pi m_1 m_2}}, \]  
(A1)

where \( m_1 \) and \( m_2 \) are the masses of the colliding aggregates, and we evaluate this by setting \( m_1 = m_2 = m \).

The differential drift velocities \( \Delta v_1 \), \( \Delta v_0 \), and \( \Delta v_2 \) are functions of the Stokes numbers \( St_1 \) and \( St_2 \) of the colliding pair, which are given by

\[ \Delta v_1 = |v_1(S t_1) - v_1(S t_2)|, \] 
\[ \Delta v_0 = |v_0(S t_1) - v_0(S t_2)|, \] 
\[ \Delta v_2 = |v_2(S t_1) - v_2(S t_2)|, \]  
(A2) (A3) (A4)

or equivalently

\[ \Delta v_{12} = |v_{12}(S t_1, A s) - v_{12}(S t_2, A s)|. \]  
(A5)

The turbulent velocity \( \Delta v_t \) has expressions (see Equations (17) and (18) of Ormel & Cuzzi (2007)) depending on the Stokes and \( Re \) numbers, where \( Re = \omega D c / \nu \) is the turbulent Reynolds number and \( \nu_{mol} = \nu_B \lambda_{mol} / 2 \) is the molecular viscosity. Note that \( \nu_B = \sqrt{8k_B T / \pi m_B} \) and \( \lambda_{mol} \) are the thermal velocity and mean free path of gas particles, respectively,

\[ \Delta v_t^2 = \Delta v_i^2 + \Delta v_{12}^2, \]  
(A6)

where

\[ \Delta v_{12}^2 = \alpha_D C_v^2 \frac{St_1 - St_2}{St_1 + St_2} \left( \frac{St_1^2}{St_1^2 + St_1} - \frac{St_2^2}{1 + St_1} \right). \]  
(A7)

and \( St_1 = \min(1.6St_1, 1) \). It should be noted that \( \Delta v_{12}^2 = 0 \) if \( St_1 \leq Re_t^{-1/2} \).

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