Dust Coagulation in a Massive Protostellar Disk

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Simulation Movie URL

1. Introduction

It is essential to understand the formation of massive stars because of their pivotal roles in galaxy evolution and the formation of stars and planets. Recently, an increasing number of discoveries of accretion disks around massive protostars have been reported (e.g., Johnston et al. 2020). More recently, **dust growth in a massive protostellar disk has been suggested by ALMA 1.14 mm polarization observation** (Girart et al. 2018). In these observations, a polarization vector pattern aligned with the minor axis of the disk and a relatively high polarization fraction of several percent were detected in the southwestern region (~ 100 au) of the GGD27-MM1 disk (the driving source of HH 80–81, Figure 1). This is a characteristic signature of dust self-scattering by grains with sizes $a_{\rm max} \sim 100\,\mu$m comparable to the observing wavelength (Yang et al. 2017), suggesting the presence of dust grains larger than those typically found in the interstellar medium $a_{\rm max} \sim 0.1\,\mu$m.

Dust growth alters the optical properties of the disk (Figure 2). **This affects submillimeter observations** and introduces uncertainties in the estimation of physical quantities such as disk temperature and mass. Additionally, **it affects key factors related to disk evolution, including cooling rate and heating efficiency.** Therefore, it is crucial to clarify the mechanisms of dust growth and its impact. In this poster, we present our ongoing research aimed at deepening this understanding.

Figure 1 GGD27-MM1

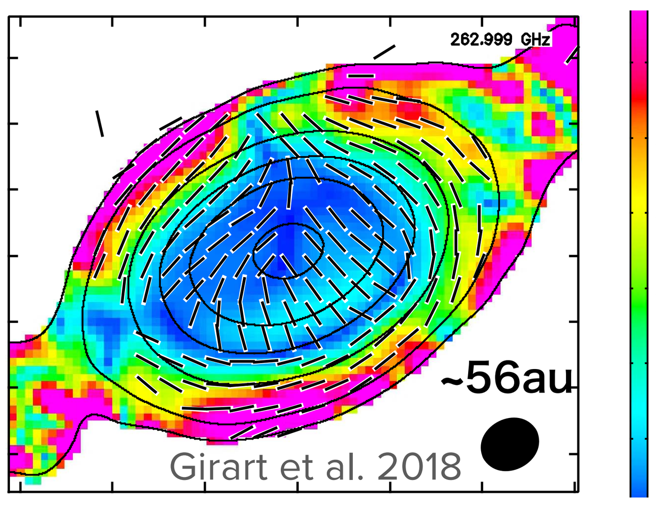
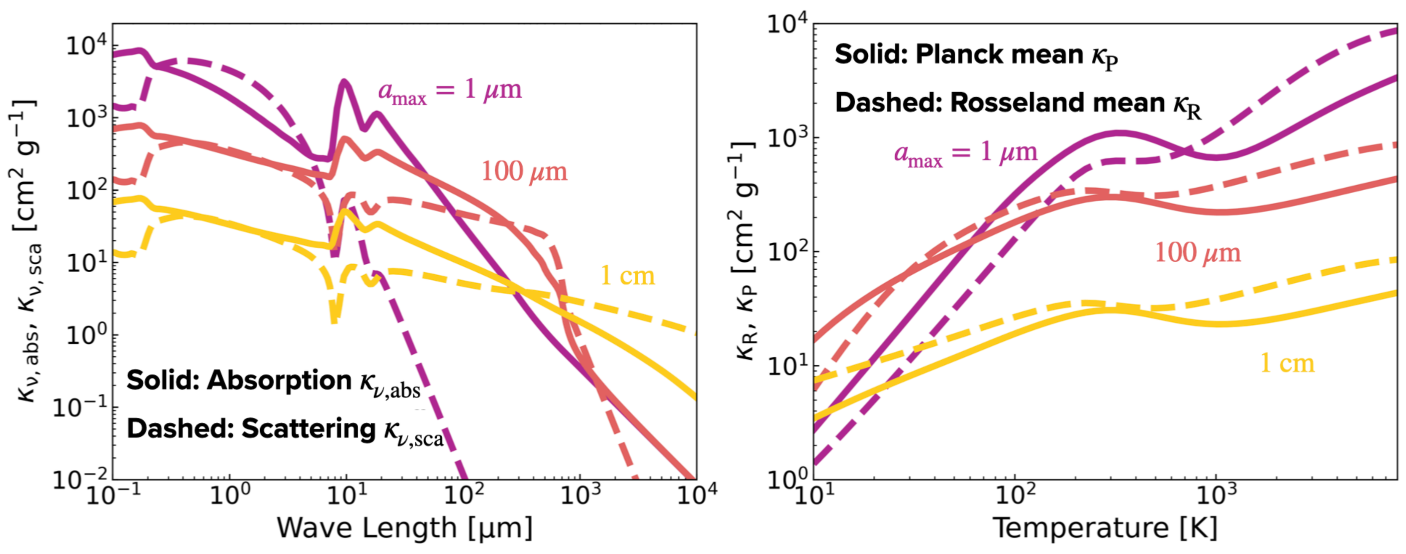


Figure 2 The opacity profile of the maximum grain radius



2. Impact of Dust Coagulation on Disk Structure

Figure 3: A schematic of our axisymmetric and steady analytical disk model, including dust evolution. To understand the picture of dust growth and its impact, we self-consistently solve the gas disk structure and dust growth from the outer edge of the disk inward, terminating at a distance 10 au from the star.

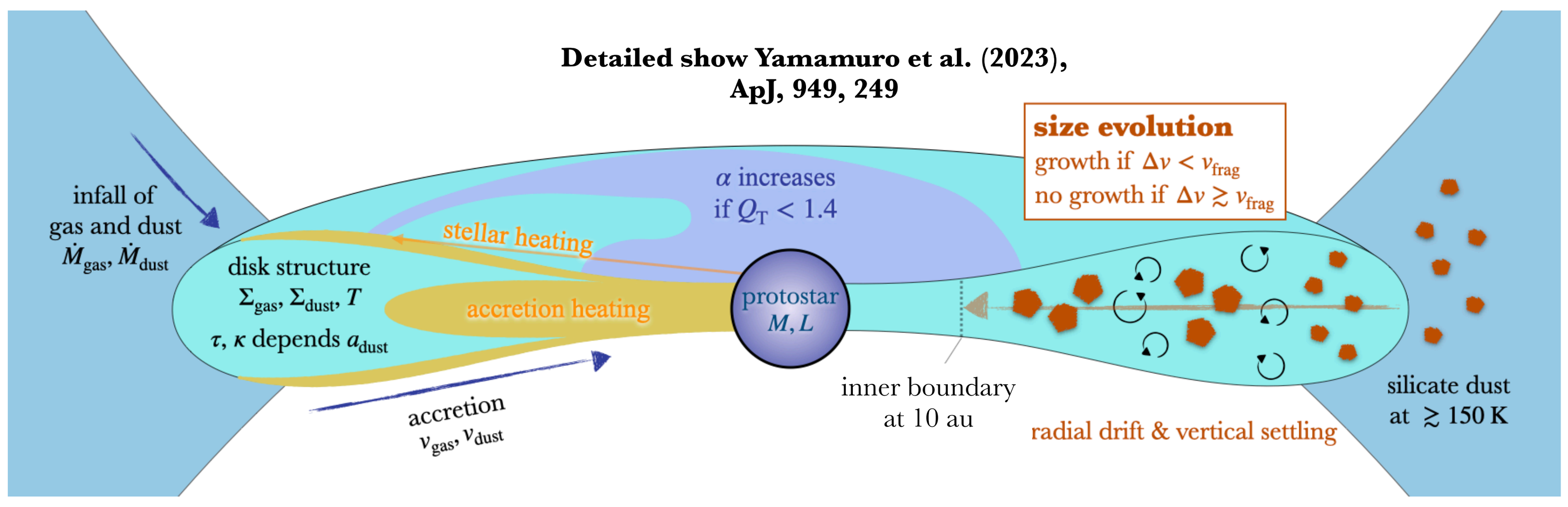


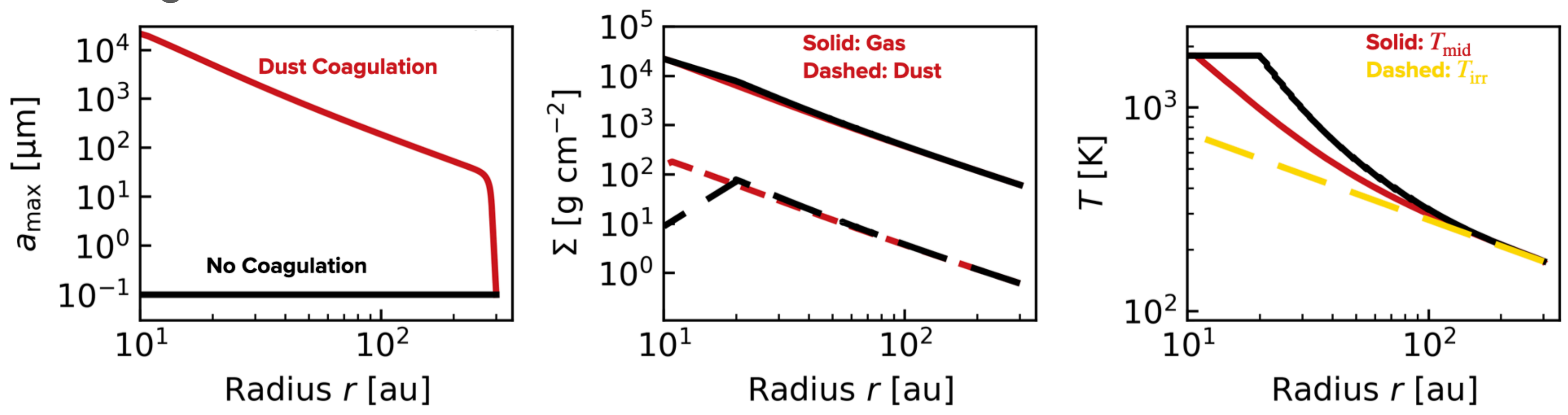
Figure 4 shows radial profiles of key physical quantities in the massive protostellar disk model. Black and red lines indicate cases without and with dust coagulation, respectively. We used parameter values assuming a massive protostellar disk, as listed in Table 1. **The results show that dust can grow even in the massive protostellar disk.** Next, we examine the impact of dust growth on the disk structure. The temperature of a massive protostellar disk is determined by both stellar irradiation and accretion heating.

Accretion heating is more effective in the optically thick disk. **Dust growth lowers the opacity, reducing the disk temperature.**

Table 1: The parameters of our disk model

$M = 20\,M_\odot$	$r_{\rm disk} = 300$ au
$L = 4 \times 10^4\,L_\odot$	$\dot{M} = 10^{-4}\,M_\odot\,{\rm yr}^{-1}$

Figure 4



3. Dust Coagulation's Effect on Disk Observation

To investigate the observational impact of dust growth, we performed radiative transfer calculations based on the dust coagulation disk model. We use the new solution, updated from solutions such as Sierra et al. (2020).

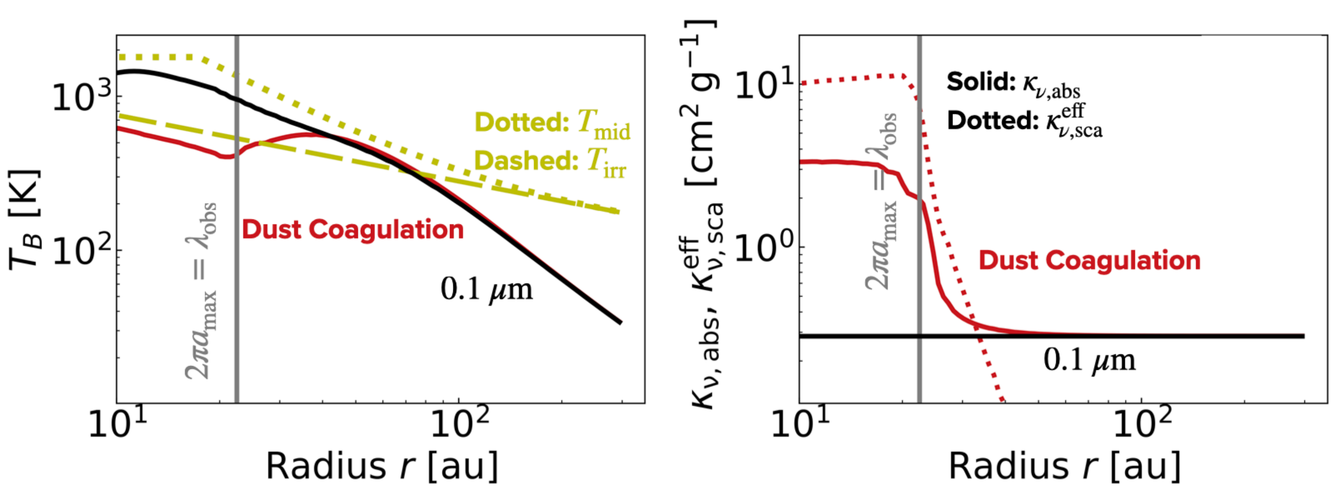
$$I_\nu(\tau_\nu) = \frac{\epsilon_\nu}{\mu}\frac{1-3\mu^2}{1-3\epsilon_\nu\mu^2}\int_0^{\tau_\nu} B_\nu(\tau_\nu')e^{-\tau_\nu'/\mu}d\tau_\nu' +$$

$$\frac{\sqrt{3}\epsilon_\nu(1-\epsilon_\nu)}{1-3\epsilon_\nu\mu^2}\,\frac{(1+\sqrt{3}\mu)-(1-\sqrt{3}\mu)e^{-\tau_{\nu,\rm tot}/\mu}}{(1+\sqrt{\epsilon_\nu})+(1-\sqrt{\epsilon_\nu})e^{-\sqrt{3\epsilon_\nu}\tau_{\nu,\rm tot}}}\int_0^{\tau_\nu} B_\nu(\tau_\nu')e^{-\sqrt{3\epsilon_\nu}\tau_\nu'}d\tau_\nu'$$

Figure 5 shows the radiative transfer results of the dust coagulation disk model (red line) and the same disk but with dust opacity $a_{\rm max} = 0.1\,\mu$m (black line).

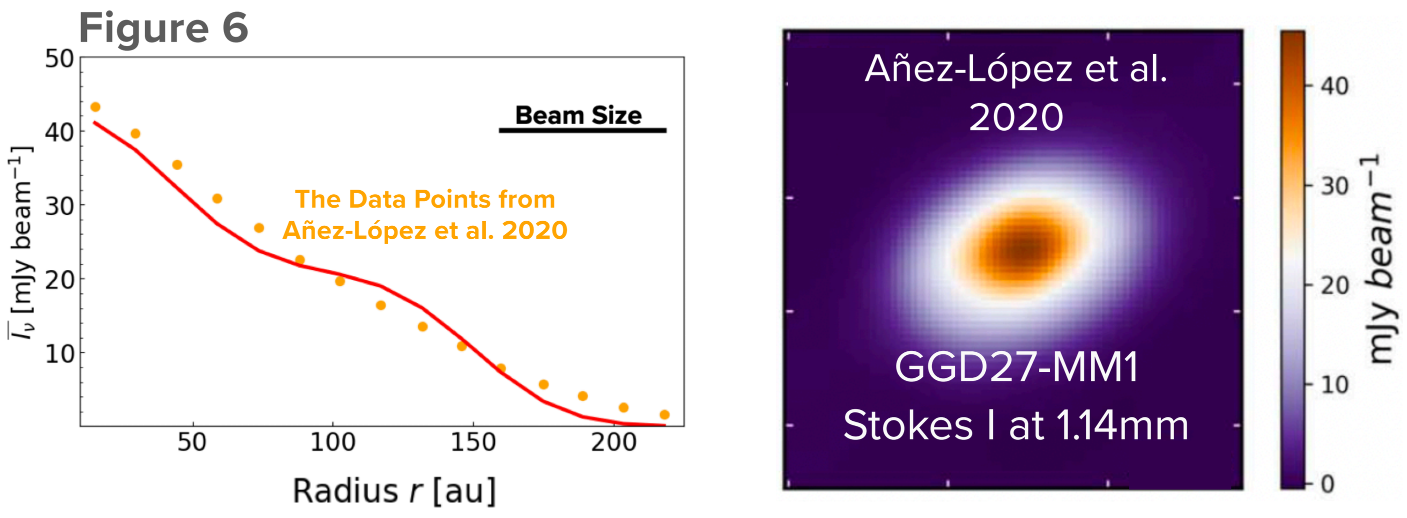
The results show that once dust grains grow to sizes exceeding the observing wavelength, enhanced opacity (especially scattering) dims the disk emission by 20–30% relative to the blackbody emission expected at the disk surface temperature.

Figure 5



To demonstrate our model, we attempt to reproduce the Stokes I emission of GGD27-MM1 (Figure 6) while maintaining consistency the dust distribution inferred from polarization, a stellar luminosity five times higher than previously assumed is required. This corresponds to the maximum luminosity explained by the flashlight effect.

Figure 6



4. Dust Coagulation's Effect on Disk Evolution

Many massive protostellar disks exhibit non-axisymmetric and time-varying structures, making it important to study how dust grows within such disks and the effects of this growth. We present results from 2D (r, ϕ) thin disk hydrodynamic simulations using FEOSAD (Vorobyov et al. 2018), which follow the collapse of a molecular cloud core and the formation of a massive protostar and its disk. FEOSAD is a simulation code that performs two-fluid calculations of gas and dust, as well as dust coagulation. It also incorporates changes in opacity associated with dust growth. Comparison with azimuthally averaged $a_{\rm max}$ values and analytical solutions from the 1D model indicates that $a_{\rm max}$ values are generally consistent within an order of magnitude inside ~ 1000 au (Figure 6).

Figure 6

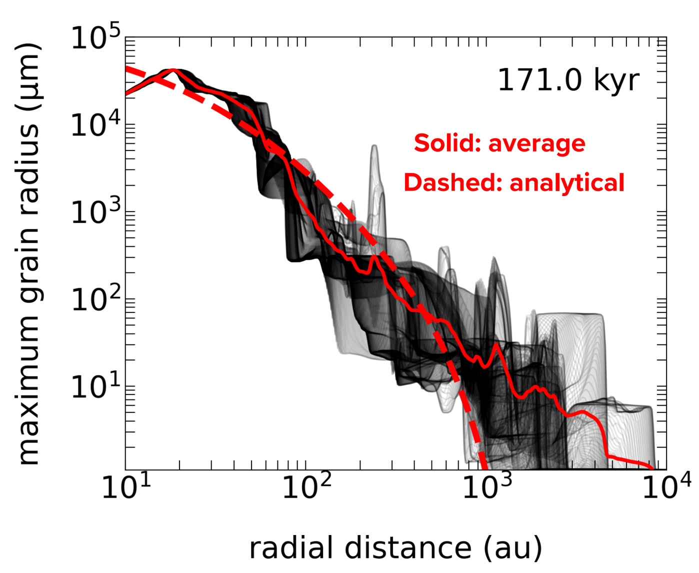
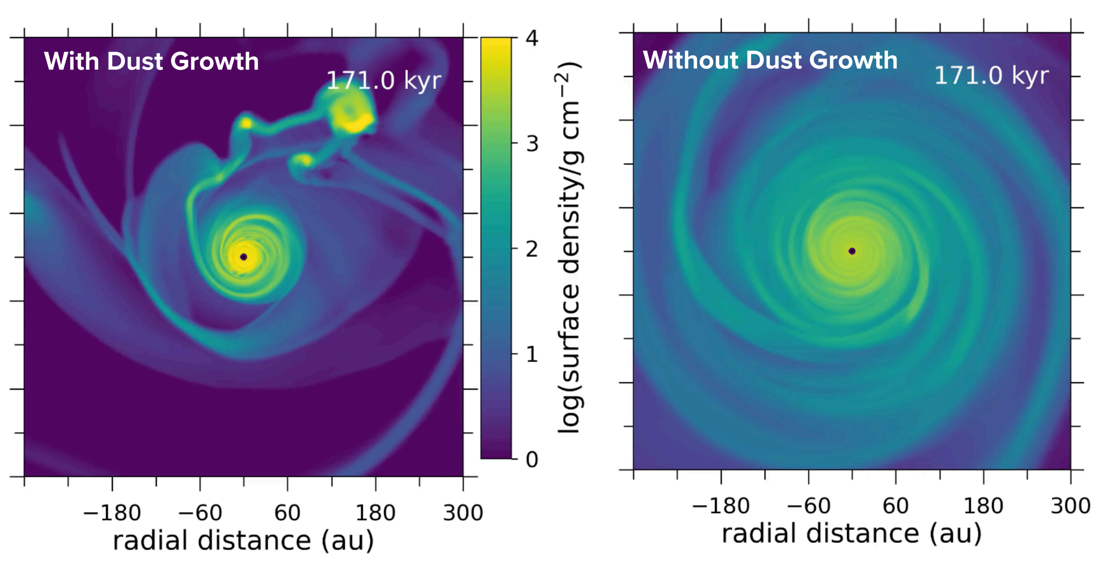


Figure 7 Impact of Dust Growth on Surface Density



The reduction of opacity due to **dust growth lowers the disk temperature. This makes the disk more gravitationally unstable** (Figure 7), **promoting disk fragmentation** driven by gravitational instability and potentially leading to binary formation. We define "clumps" as gravitationally bound cells (Matsukoba et al. 2022), and we evaluate the number of such fragments formed (Figure 8). **The disk with dust growth shows more frequent fragmentation than the one without.** Notably, when dust has grown, fragmentation occurs inside 300 au due to the reduced effectiveness of accretion heating. In contrast, the disk without dust growth fragments little in this region where accretion heating remains effective.

Figure 8