

A STUDY OF SPATIAL DISTRIBUTION
AND OPTICAL PROPERTIES OF DUST GRAINS
IN A PROTOPLANETARY DISK

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A dissertation submitted to
the Graduate School of Science and Engineering
for the degree of Doctor of Science

Ibaraki University

April 2017

Acknowledgements

The Thank You Awards ceremony.

Firstly, the Best Director winner Munetake Momose. I owe my advisor Professor Momose a great debt of gratitude. This thesis would never have been accomplished if it had not been for his continuous support and excellent guidance throughout my PhD life. I will always remember how he generously spent time discussing my thesis and staying late into the night devising ALMA proposals together. I could not wish for a better mentor for my PhD study.

Best Leading Actor. Tomoyuki Hanawa, Takayuki Muto, and Takashi Tsukagoshi are my co-authors and excellence researchers from whom I have learned a lot. Professor Hanawa taught me the basic of M1 method of radiative transfer, and kindly provided all the disk models used in this thesis. Let's not forget the tremendous efforts he has contributed to the better grammar and structure of my submitted paper. I am inspired by Associate Professor Muto, who always knows how to put complex ideas into layman's terms, which is much appreciated for a noob like me. Associate Professor Tsukagoshi is the guru you rely on whenever you became frustrated with CASA and ALMA OT. It is my utmost pleasure working with them.

Equally charming are Hideko Nomura, who shared the dust opacity tables, and the members of the thesis committee, Tatsuo Yoshida, Tooru Tsuribe, and Hidekazu Tanaka, whose hard-hitting yet insightful comments vastly improved this thesis.

Collegial life was fancily decorated by, past and present, Best Supporting Actors and Actresses. They play the roles of morose and merry, selfish and generous, composed and exuberant, anxious and carefree, satisfied and ambitious, serious and witty, bold and timid, gullible and cynical boys and girls. And in the mixed bag a mischievous and meddlesome me. I admire the way they are and relish the moments of studying and hanging out together. It was a remarkable ride having them as company.

Best Original Score. I love listening to film score. And the award goes to Aya E. Higuchi. Thank you for paying attention to my progress and thank you for always wearing the most alluring smile. Takafumi Nemoto, you won the booby prize for not understanding Tom and Summer. I will punch you right in the face if you don't ask me to be your best man, or anything equivalent in a Japanese wedding, if that matters.

My family won The Award for Best Picture. The unconditional love, that I have always been taking for granted, is the purest nutrient nourishing me ever since I set foot in this country. A discordant voice always sounds louder than a melodious tune, so strain your ears for the intended harmony.

Abstract

In the early stage of stellar evolution, circumstellar disks are formed around low to intermediate mass protostars as a natural consequence of the conservation of angular momentum during the infall of material from the molecular cloud. Just like in the interstellar medium, the disks are composed of gas and a fraction of solid particles, or dust grains, but in the denser environment of the disks the grains encounter more frequent mutual collisions that will lead to their growth in size. The growing dust grains would become the seeds of planets, and thus the disks are commonly known as protoplanetary disks. The opacity of the grains changes with their size, and in the submillimeter and longer wavelengths the scattering by the grains is simulated to be dominant over the absorption, i.e., the albedo is high, when the grain size is comparable to the wavelength of the incident light. However, in modeling the dust continuum emission at the long wavelengths the scattering is often omitted for its properties are still not well understood.

The only way to examine the nature of dust grains in the protoplanetary disks is to include simulated grains properties in the process of modeling observational data, which is where this thesis is grounded on: this work aims at determining the dust grains surface density of the crescent protoplanetary disk around a pre-main sequence, Herbig Fe star HD 142527, by taking both the absorption and the scattering of dust grains into consideration when modeling the dust continuum emission at $\lambda_{\text{obs}} = 890 \mu\text{m}$ obtained by the Atacama Large Millimeter/submillimeter Array (ALMA). The opacity is of the conventional values calculated by the Mie theory for compact, spherical dust grains composed of silicate, carbonaceous compounds, and water ice of solar elemental abundance. The number distribution of the grains depends on the size radius a as $n(a) \propto a^{-3.5}$, where the maximum size is 1 mm. In this dust configuration, the scattering opacity is about ten times higher than the absorption opacity at the modeling wavelength. The ALMA continuum emission map at $890 \mu\text{m}$ is divided into 18 sectors, and the radial intensity profile in each sector is reproduced with a two-dimensional, axisymmetric disk model whose radiative transfer is calculated by the M1 method. The model intensity depends on the azimuthal direction after taking the disk inclination $i = 27^\circ$ into account.

When the dust is assumed to have the conventional opacity values, the emission in the northwest region of the disk in $PA = 291^\circ - 351^\circ$ cannot be reproduced, because the model intensity hits a limiting value, or the intensity ceiling, that is much lower than the observed intensity. This is a consequence of heavy scattering that not only lowers the intensity from that of a blackbody radiation but also causes the model intensity to become insensitive to the increase of surface density when the disk model is optically thick. By reducing the scattering opacity by 90% across the wavelengths its value becomes comparable to that of the absorption

at the modeling wavelength, and the raised intensity ceiling not only allows the emission in the northwest region to be successfully reproduced, but it also estimates lower surface density values for other optically thick sectors in the northern region of the disk. Contrarily, the results derived by the reduced opacity model for the southern, optically thin region of the disk are seen to be depending less on the scattering opacity.

The different outcomes by the two opacity models might be consistent with the large-scale vortex scenario that explains the crescent structure of the disk around HD 142527, in which case the grains will distribute differently in the azimuthal direction based on their size. Or, their results might suggest the inappropriate assumption of dust grains as compact spheres, and one needs to focus on the optical properties of aggregates composed of numerous submicron particles instead. Although no firm conclusion can be made at this stage, this work suggests that the scattering of dust grains may be somehow lower than expected in the submillimeter and millimeter wavelengths, whose cause is most likely to be coming from the underdetermined chemical composition and structure of the grains. In future, multi-wavelength observations complemented with detailed modeling will become essential to address the unsolved issues of grain size as well as any undiscovered detailed structures of the disk.

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Chapter 1

Introduction

The first discovery of an exoplanetary system was made in 1995: a planet was found orbiting the main-sequence star 51 Pegasi ([Mayor and Queloz, 1995](#)). The planetary system is 51 light years away from our Solar System and it became the first evidence that our own system is not alone in the Universe. In fact, the number of discovered exoplanets has been growing ever since, by virtue of the ground-based High Accuracy Radial velocity Planet Searcher (HARPS) ([Mayor et al., 2003](#)) and the *Kepler* space telescope ([Borucki et al., 2010](#)). As of April 2017, there are 3483 planets and 581 multiple planetary systems confirmed, as well as 4496 candidate planets discovered ([NASA Exoplanet Archive](#)). The recent findings of a habitable terrestrial planet around Proxima Centauri ([Anglada-Escudé et al., 2016](#)) and seven others in the TRAPPIST-1 system ([Gillon et al., 2017](#)) could be signs of extraterrestrial life in the part of Universe unexplored by mankind.

The 51 Pegasi planetary system was thought to be bizarre compared to the Solar System. The planet, 51 Pegasi b, is a gas giant about half the mass of Jupiter, yet it orbits the star 51 Pegasi, which has a similar mass as the Sun, at a distance of about eight million kilometers, or 0.05 au; it is well within the 0.4 au orbital radius of our innermost rocky planet Mercury. 51 Pegasi b is then dubbed as a “hot Jupiter”, a term for Jupiter-like planets orbiting at 0.1 au or less from their host stars. Subsequent discoveries find other exotic planets such as the “super Earths” and “super Jupiters”; we then realized that the mass and orbital radius distributions of the exoplanets are way different from our Solar System. In parallel with seeking for other life forms and possible habitable zones, we are also going after for scientific explanations for the diversity of exoplanets. This naturally leads us to the studies of protoplanetary disk, which consists of gas and solid particles that surround newborn stars and is considered to be the birthplace of planets.

As an introduction to the dissertation, this chapter first gives a brief summary of the star formation. This will be followed by an overview of the protoplanetary disks, which will mainly cover the spatial distribution and the properties of solid particles residing within.

1.1 Overview of star formation

The space between stars, or the interstellar space, is not a perfect vacuum void of material. It consists of atomic, molecular, and ionized matter, with the most abundant species being hydrogen that composes 70% of the total mass of the medium, followed by helium that fills up 28%. The remaining fraction is of the elements heavier than the abundant species,

such as carbon, oxygen, and nitrogen, which are commonly known as metals. Most of the matter is in the gas phase, although there is about 1% of the total mass that resides in sub-micron or micron-sized solid particles. Altogether, the gas and solid components are referred as the interstellar medium (ISM). The ISM is not homogenous in its existence; it achieves a phase of equilibrium between heating from the environment and cooling of the medium itself. Therefore, the temperature and density as well as the chemical state of the matter varies accordingly to the heating-cooling balance. The various thermal phases of the ISM are categorized in [Table 1.1](#). Even in the molecular phase the ISM is tenuous when compared to the Earth’s atmosphere, whose number density is $n_{\text{tot}} \sim 10^{19} \text{ cm}^{-3}$ at sea level.

Table 1.1: Phases of the interstellar medium.

Phase	$n_{\text{tot}} \text{ (cm}^{-3}\text{)}$	$T \text{ (K)}$	$M \text{ (}\times 10^9 M_{\odot}\text{)}$	f
Molecular	> 300	10	2.0	0.01
Cold neutral	50	80	3.0	0.04
Warm neutral	0.5	8×10^3	4.0	0.30
Warm ionized	0.3	8×10^3	1.0	0.15
Hot ionized	3×10^{-3}	5×10^5	–	0.50

The number density, temperature, mass, and volume filling factor are denoted by n_{tot} , T , M , and f , respectively. The values are characteristic values in our Milky Way galaxy.

Adapted and modified from Table 3.1 of [Stahler and Palla \(2005\)](#). See also [Ferrière \(2001\)](#).

The molecular medium can be categorized into giant molecular clouds (GMC) and dark clouds¹; in average, both are usually $\sim 500 \text{ g cm}^{-3}$ in number density and $\sim 10 \text{ K}$ in temperature. The GMCs are typically about $10^5 M_{\odot}$ in mass and 50 pc in size, larger and more massive compared to the dark clouds which measure 10 pc and $10^3 M_{\odot}$. Most often, terms like clumps and cores are used to indicate the more mass-concentrated regions within the clouds. These structures are gravitationally bound entities about 3 pc or less in size and 10^3 g cm^{-3} in number density, although the cores are typically three orders of magnitude higher in density. The clumps and cores, being the deepest regions of the molecular ISM, are where the star formation takes place. The GMCs as in the Orion molecular clouds give birth to multiple massive stars (mass more than eight times the solar mass), in contrast to the dark clouds such as those in Taurus that form only isolated, low mass stars.

The formation mechanism of stars heavier than $8 M_{\odot}$ is less well established. The first reason being the small sample of high-mass stars; the population falls steeply with mass as predicted by the initial mass function, a function describing the relative number of stars produced per unit mass interval ([Salpeter, 1955](#); [Chabrier, 2005](#)). As a result, the forming regions of high-mass stars usually distribute several kiloparsecs away from us, so far that high-angular-resolution is required to study them in detail. The short evolutionary timescale of the high-mass stars is another limiting factor. A measure for the timescale is the Kelvin-Helmholtz time t_{KH} , defined as the timescale where the gravitational energy is radiated away

¹See, e.g., Table 1.1 of [Purcell \(2007\)](#) for more detailed categorization of clouds.

as heat in the rate of star luminosity L_* ,

$$t_{\text{KH}} \equiv \frac{GM_*^2}{R_*L_*} = 3 \times 10^7 \text{ yr} \left(\frac{M_*}{M_\odot} \right)^2 \left(\frac{R_*}{R_\odot} \right)^{-1} \left(\frac{L_*}{L_\odot} \right)^{-1}, \quad (1.1)$$

where G is the gravitational constant, M_* and R_* the stellar mass and radius, respectively. The solar mass, radius, and luminosity are denoted by $M_\odot$, $R_\odot$, and $L_\odot$, respectively. Stars heavier than $8 M_\odot$ is predicted to have $t_{\text{KH}} \lesssim 10^5 \text{ yr}$ ². As will be described later, the gravitational collapse of a parent cloud forming stars takes about 10^6 yr . Therefore, the formation timescale of high-mass stars is so short that the stars reach the main-sequence while they are still being deeply embedded in the cloud of gas and dust that obscure observations even at the radio wavelengths, not to mention direct visual. Indirect method such as the bright masers emission in the vicinity of the stars has been intensely observed, and theoretical studies show that it can be related to the dynamics of the deeply embedded objects (Araya et al., 2010; van der Walt, 2011; Inayoshi et al., 2013)

Stars of several solar masses or less, on the other hand, have a generally accepted formation scenario, and to a certain extent the scenario may be applied to the higher-mass counterparts. It all starts from the gravitational collapse of a dense core that happens on the timescale of the free-fall time t_{ff} , i.e., the time for a spherical cloud to collapse to the center by its self-gravity in a pressure-free condition (see, e.g., Bodenheimer and Sweigart, 1968; McKee and Ostriker, 2007), and by definition it is a function of the medium density ρ following

$$t_{\text{ff}} = \left(\frac{3\pi}{32G\rho} \right)^{1/2} = 1.37 \times 10^6 \text{ yr} \left(\frac{n_{\text{tot}}}{10^3 \text{ cm}^{-3}} \right)^{-1/2}. \quad (1.2)$$

The core contraction is initially isothermal, but eventually at the center of the core the density rises to $\rho_c \sim 10^{-13} \text{ g cm}^{-3}$ and it becomes opaque to its own cooling via infrared radiation (Masunaga, Miyama, and Inutsuka, 1998; Masunaga and Inutsuka, 2000). Further addition of mass and shrinking of the core radius results in the increase of temperature that surpasses 2000 K at $\rho_c \sim 10^{-7} \text{ g cm}^{-3}$, leading to the collisional dissociation of the molecular hydrogen H_2 . Subsequently, the internal core achieves hydrostatic equilibrium that prevents any further gravitational collapse, and continues gaining mass from the enveloping cloud. The core is now known as the protostar, gradually contracting in size and blowing away the envelope to become a pre-main sequence-star. pre-main sequence stars are called T Tauri stars if their mass is $M_* \lesssim M_\odot$, Herbig stars if they are $M_\odot < M_* < 8M_\odot$. At last, the young stellar object (YSO) evolves into a main-sequence star once hydrogen fusion ignites in the star interior at 10^7 K , marking the end of star formation.

The evolutionary stages of the low-mass YSOs, from the core collapse to the stage before hydrogen fusion ignition, are categorized into Class 0, I, II, and III based on their slopes on the spectral energy distributions (SEDs) in the infrared region between $2 \mu\text{m}$ and $25 \mu\text{m}$,

$$\alpha_{\text{IR}} = \frac{d \log \nu F_\nu}{d \log \nu} = \frac{d \log \lambda F_\lambda}{d \log \lambda}, \quad (1.3)$$

²By the empirical mass-luminosity relation (Kuiper, 1938; Eker et al., 2015), $L \propto M^a$ where a is a positive index that depends on the stellar mass. The exponent is $a \approx 3$ for stars of a few tens of solar mass.

Table 1.2: Classification of YSOs.

Class	SED slope	Physical properties	Observational characteristics
0	—	$M_{\text{env}} > M_* > M_{\text{disk}}$	No optical or near-IR emission, main accreting phase from infalling envelope.
I	$\alpha_{\text{IR}} > 0.3$	$M_* > M_{\text{env}} \sim M_{\text{disk}}$	Generally optically obscured.
FS	$-0.3 < \alpha_{\text{IR}} < 0.3$		Flat spectrum class (Greene et al., 1994), intermediate between Class I and II.
II	$-1.6 < \alpha_{\text{IR}} < -0.3$	$M_{\text{disk}}/M_* \sim 1\%$, $M_{\text{env}} \sim 0$	Accreting disk, strong H α and UV.
III	$\alpha_{\text{IR}} < -1.6$	$M_{\text{disk}}/M_* \ll 1\%$, $M_{\text{env}} \sim 0$	Passive disk, no or very weak accretion.

The masses of the star, disk, and envelope are denoted by M_* , M_{disk} , and M_{env} , respectively.

Adapted and modified from Table 1 of Williams and Cieza (2011).

as shown in Figure 1.1 and Table 1.2 (Lada, 1987; Andre, Ward-Thompson, and Barsony, 1993). The classification is also one that follows the chronological order of stellar evolution from the gravitational collapse of a molecular core to the pre-main sequence star. The Class 0 YSOs manifest themselves as gray-body radiators of ~ 10 K at the millimeter and submillimeter. It is in this phase that circumstellar disks form around the YSOs; this is a result of the conservation of angular momentum inherited from the contracting core, rotational energy of which is estimated to be about 2% of the gravitational energy (Goodman et al., 1993). In subsequent classes an emission excess in the infrared compared to the stellar blackbody radiation can be seen, which results in $\alpha_{\text{IR}} > -2$. The excess is a consequence of the material surrounding the central star, i.e., the circumstellar disk, that has a wide range of temperature from ~ 100 K to ~ 300 K. At the earlier Class I and Class II the luminosity of the disks can be greater than the central stars, implying the high optical thickness as well as the young age of the disks.

The infalling of material from the envelope during the Class 0 and Class I phases will determine the total mass of the star, as mass gained via disk accretion in subsequent evolution is a small fraction for the disk mass is usually only a few percents of the stellar mass. The disk accretion requires that the accreting gas to lose its angular momentum, by either redistributing it through turbulence-induced viscosity (Shakura and Sunyaev, 1973; Hartmann et al., 1998; Hartmann, Herczeg, and Calvet, 2016) or magnetorotational instability (MRI) (Gammie, 1996; Balbus and Hawley, 1998), or by disk winds (Pudritz and Norman, 1983; Konigl, 1989). As the evolution proceeds the surrounding envelope becomes optically thin after transferring most of its mass to the star-disk system meanwhile being dispersed by outflow activities originated from the stars, therefore the inner system is gradually exposed at the visible spectrum. For T Tauri stars, the circumstellar disks remain for $\sim 10^6$ yr and serve not only to deliver material to the growing stars, but also have an important role in the possible planet formation.

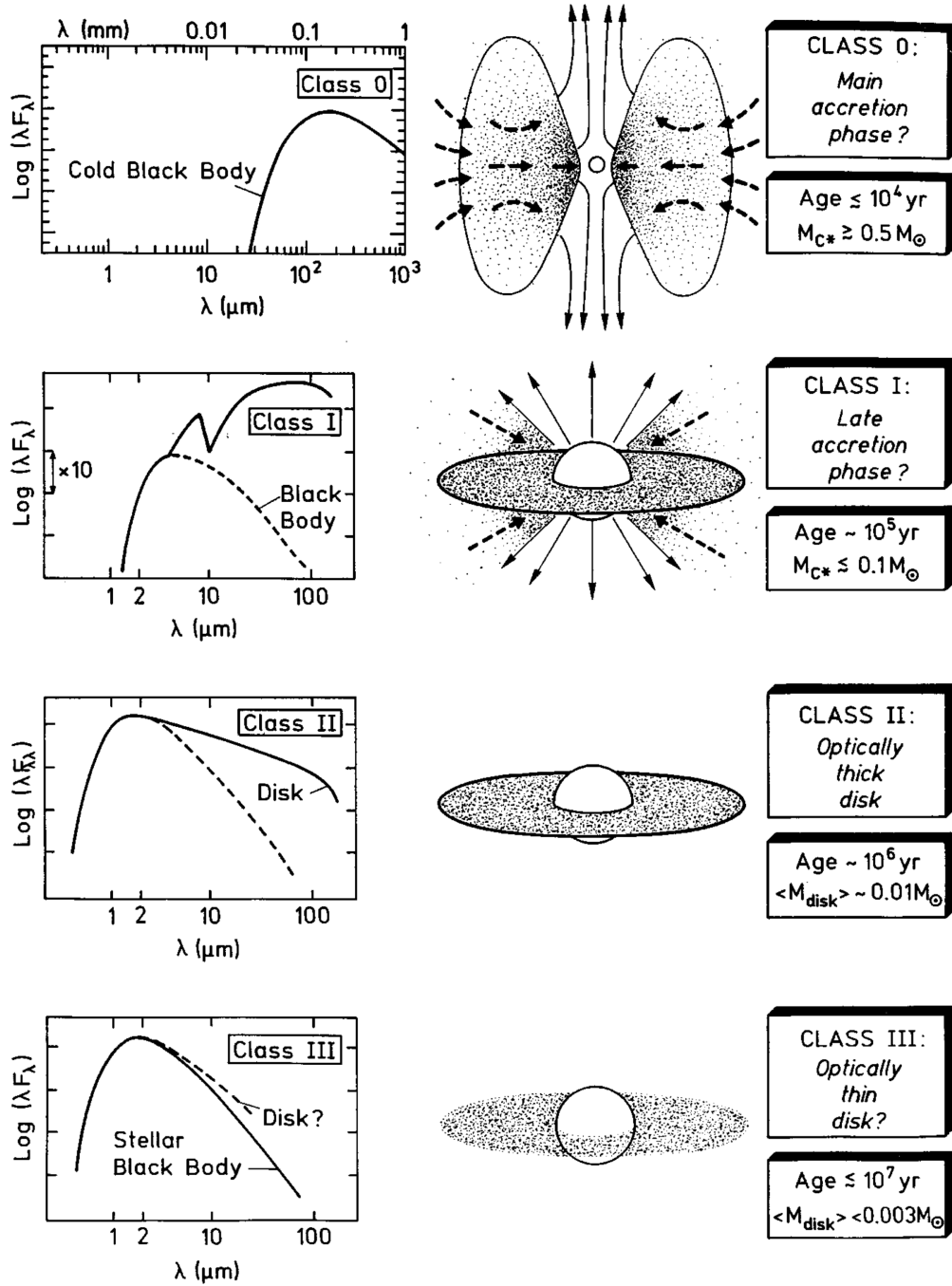


Figure 1.1: Classification of YSOs into Class 0, I, II, and III, from the earliest evolutionary stage as a protostar deeply embedded in the molecular envelope to the later stage as a pre-main sequence star where the envelope as well as the circumstellar disk is dispersed. The plots on the left show the SEDs (flux plotted against wavelength), while the illustrations in the center visualize the circumstellar environment of each class. The physical scale in the illustration is approximately ~ 5000 au in Class 0, ~ 500 au in Class I, and ~ 100 au for the rest.

Adapted from Figure 11 in [Bachiller \(1996\)](#).

1.2 Protoplanetary disk

1.2.1 Morphology

At Class 0 the circumstellar disks form around the stars are known as the protostellar disks, so named as they function to transfer mass onto the stars via viscous accretion. As the mass accretion rate decreases towards the end of Class 0, other activities begin to significantly sculpture the disks, such as photoevaporation, radial motion and vertical settling of dust grains, and dynamical interactions with stellar or substellar objects. Most of all, the gravitational instability and the agglomeration of the dust grains are considered to be the pathways leading to planetesimal formation; thus, after Class 0 the disks are referred as the protoplanetary disks.

The appearance of the protoplanetary disks depends on their evolutionary states. As shown in [Figure 1.2](#), they can be classified into full disks, pre-transitional disks, and transitional disks. The full disks are the youngest among them, and their smooth radial distributions of dust and gas can be approximated by the similarity solution for the evolution of a viscous accretion disk ([Hartmann et al., 1998](#)). A schematic for the full disk is shown in [Figure 1.3](#). In the full disk the dust grains distribute down to a radius of several stellar radius (~ 0.05 au), where typically the grains sublime due to the heating by the star. In the pre-transitional disk, a gap exists and it divides the disk into the inner disk and the outer disk. Although the transitional disks does not possess an inner disk, a hole, or cavity, between the star and the outer disk is seen. The gap and the cavity indicate that the region is optically thin, devoid of small dust grains (sizes smaller than 1 μm) which have high emissivity ([Miyake and Nakagawa, 1993](#)). Photoevaporation by the central star ([Gorti, Hollenbach, and Dullemond, 2015](#)), grain growth ([van Boekel et al., 2005](#); [Dullemond and Dominik, 2005](#); [Tanaka, Himeno, and Ida, 2005](#)), or planet-disk interactions ([Zhu et al., 2011](#); [Kanagawa et al., 2015](#); [Kanagawa et al., 2016](#)) may be responsible for the removal of small dust grains in the cavity. The first two mechanisms, however, occur predominantly inside-out in the disk radial direction, contradicting the survival of the inner disk. The existence of one or more planets that carve the gap structures is thus favored for the pre-transitional disks ([Espaillat et al., 2010](#)).

Two examples of protoplanetary disks observed at the submillimeter wavelengths are shown in [Figure 1.4](#). SAO 206462 is a Herbig Ae/Be star of mass $\sim 1.7 M_{\odot}$, located at 142 pc away in the Sco-OB2 association, while SR 21 is a G3 star of mass $\sim 2.5 M_{\odot}$ located at 119 pc in the ρ -Ophiuchus. In the dust continuum emission, both disks show cavity in the inner region that will classified them as the transitional disk. The continuum emission is not axisymmetric with respect to the central star, indicating that the dust grains accumulate at the brighter region. In contrary, the gas distributes down to a region close to the star and is more symmetric compared to the dust emission. From the observations, we know that the gas and dust in the protoplanetary disks may not distribute alike, indicating the different dynamics of them as they collapse to form the disk.

Before the era of high-angular-resolution interferometry such as the Atacama Large Millimeter/submillimeter Array (ALMA), the SEDs of YSOs have been the essential clues to interpret the morphology of the disks. The copious emission in the infrared and longer wavelengths cannot be attributed to the photosphere of the central star ([Strom et al., 1989](#);

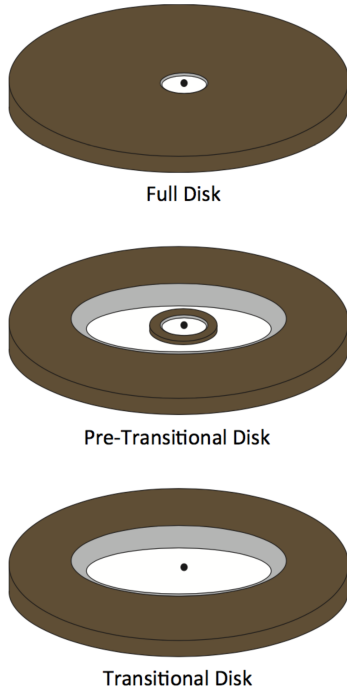


Figure 1.2: Categorization of protoplanetary disks according to the spatial distributions of dust grains. The black sphere indicates the central star, while the brown region indicates the dust grains residing in the disk. The light gray region is the disk surface, or wall, facing the star. The cavity seen in the vicinity of the star in the full and pre-transitional disk is a consequence of dust grains sublimation. In the pre-transitional disk, the disk is further divided into the inner disk and the outer disk by a gapped region. The transitional disk, on the other hand, does not harbor an inner disk.

Adapted from Figure 2 in [Espaillat et al. \(2014\)](#).

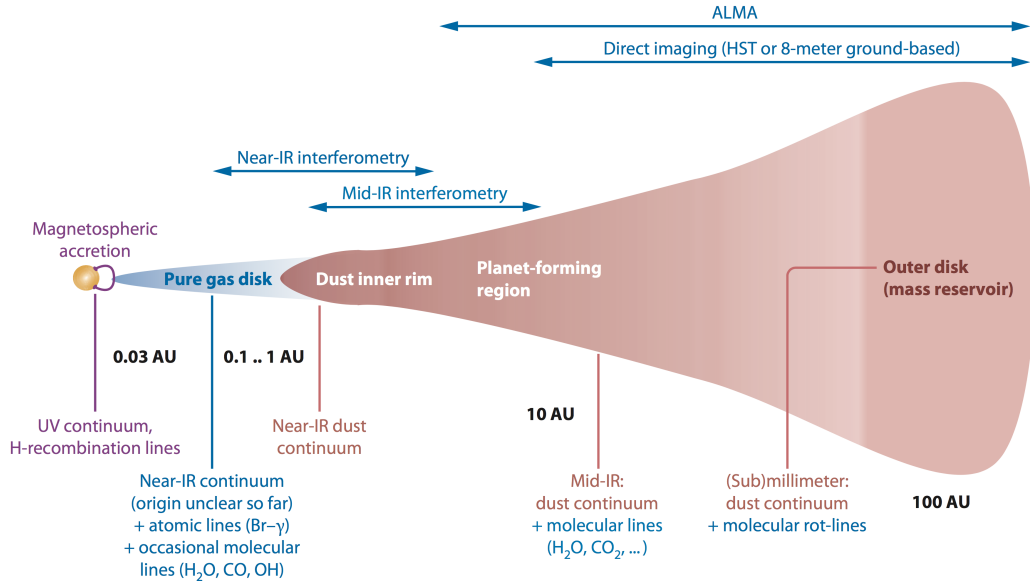


Figure 1.3: Schematic cross section of a protoplanetary, full disk. The yellow sphere on the left is the central star, while the blue and brown shaded regions are the protoplanetary disk composed of gas and dust. The radial scale on the horizontal axis is not linear. The double-headed arrows show the resolving power of each of the observational techniques at a distance of approximately 150 pc. Descriptions below the schematic explain the origins of the emissions in the disk. The schematic represents a full disk; in the SED, the near-infrared and mid-infrared fluxes come mostly from the surface layer of the disk inner region near to the star, while millimeter and submillimeter fluxes come from the disk outer region, as well as from the disk midplane, which is opaque to the stellar radiation in the early evolutionary state and does not get heated up as much as the surface layer.

Adapted from Figure 1 in [Dullemond and Monnier \(2010\)](#).

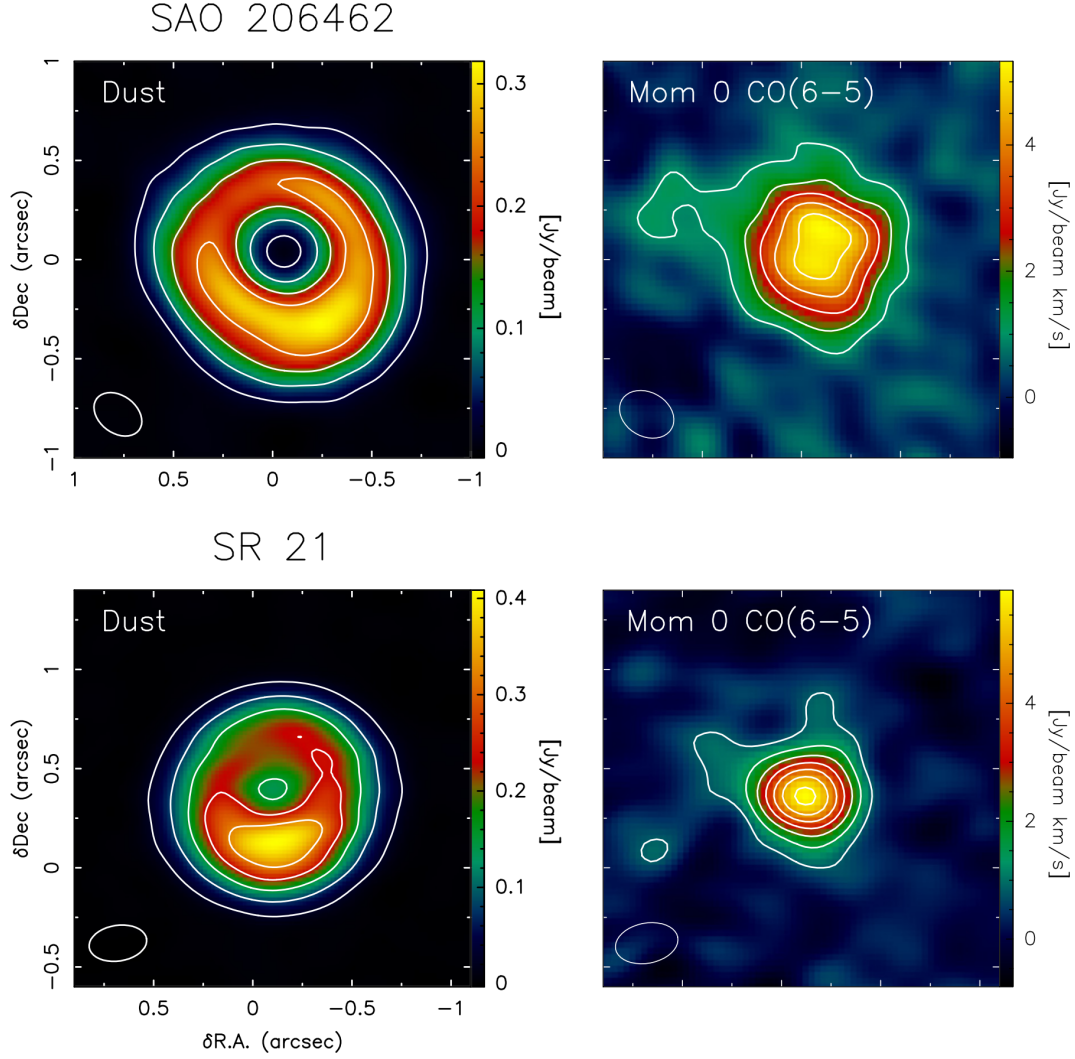


Figure 1.4: Images of two protoplanetary disks at $450 \mu\text{m}$ obtained by ALMA in Cycle 0. In the top row the results of SAO 206462 while in the bottom row that of SR 21, disk system of approximate age of 8 Myr and 3 Myr, respectively. The left panels are the dust continuum emission while the right panels are the moment 0 map of $^{12}\text{CO } J=6-5$ line emission. The eclipses in the left bottom of each panel is the synthesized beam. Adapted from Figure 1 in Pérez et al. (2014).

Weintraub, Sandell, and Duncan, 1989), which is typically $\sim 4000 \text{ K}$ or higher and thus will peak at the visible spectrum. The continuum excess suggests that the YSOs exhibit a wide range of temperatures, in which the hotter, optical radiation comes from the stars while the infrared and millimeter emissions originate from colder regions of $\sim 300 \text{ K}$ or less, i.e., the then observationally unresolved disks. Some examples of the SEDs are shown in Figure 1.5; within the figure the short-dashed plot is the median SED inferred from low-mass star ($\sim 1 M_{\odot}$) forming sites in Taurus-Auriga molecular cloud, which are considered to be young ($< 1 \text{ Myr}$) so that the circumstellar disks are of the full disk and are optically thick. From the plots, it is clearly seen that the SED slope index α_{IR} is greater than the -2 slope of the blackbody radiation of the stellar photosphere in the Rayleigh-Jeans regime. Compared to a full disk, the pre-transitional and transitional disks show a steeper slope that is accom-

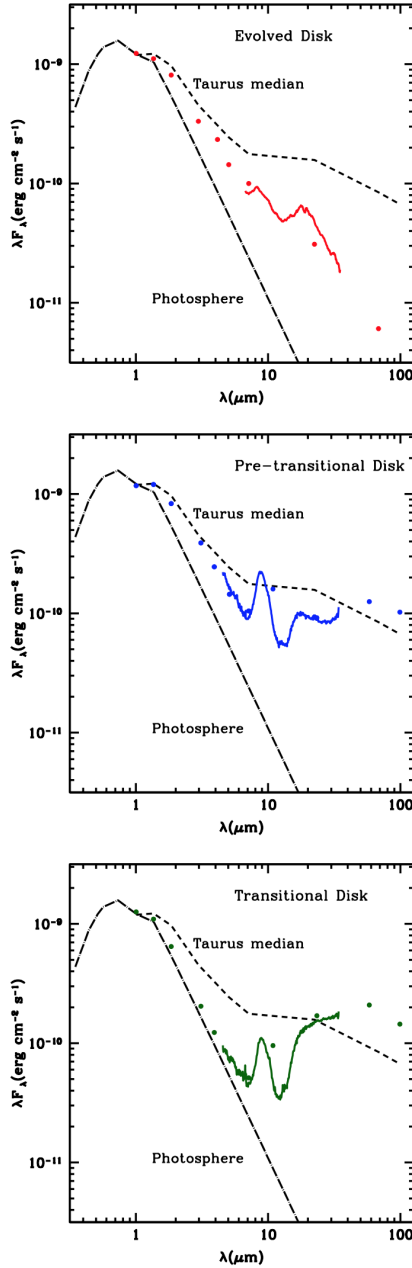


Figure 1.5: From top to bottom, the SEDs of an evolved disk RECX-11 (Ingleby et al., 2011), a pre-transitional disk LkCA 15 (Espanlat et al., 2007), and a transitional disk GM Aur (Calvet et al., 2005), are shown. The dot-long-dashed line is the blackbody spectrum of the central stars of spectral type K3–K5, while the short-dashed line is the median SED inferred from observations of star forming regions in Taurus-Auriga molecular cloud (D’Alessio et al., 1999; Kenyon and Hartmann, 1995), which is taken as a representative SED of an optically thick full disk. The solid dots and lines are the observational results. The local peak at around $10\ \mu\text{m}$ is an emission feature of silicate. RECX-11 is a rather interesting disk of age 5 Myr – 9 Myr, a state of which the disk would have been dissipated.

Adapted from Figure 1 in Espanlat et al. (2014).

panied by a dip in the infrared regime between $5\ \mu\text{m}$ and $20\ \mu\text{m}$ (Strom et al., 1989; Skrutskie et al., 1990). This is the characteristic SEDs of the pre-transitional and transitional disks (Muzerolle et al., 2010; Andrews et al., 2011), which is interpreted by models as the deficit of dust grains in the disk region corresponding to the infrared wavelengths (Calvet et al., 2002; Calvet et al., 2005). The dust-depleted regions are indeed confirmed observationally as the gaps and cavities (Brown et al., 2009; Grady et al., 2015).

1.2.2 Azimuthal-asymmetric protoplanetary disk

Observations at the radio wavelengths revealed several protoplanetary disks that are non-axisymmetric in their dust continuum emission, i.e., in the azimuthal direction the surface

brightness varies significantly. For example, the surface brightness contrast ranges from a factor of a few in the outer disks of LkH α (Isella et al., 2013) as well as SAO 206462 and SR 21 shown in Figure 1.4 (Pérez et al., 2014), to about 30 in HD 142527 (Casassus et al., 2013; Fukagawa et al., 2013). In particular, in the IRS 48 disk system the contrast reaches a striking value of 130 (van der Marel et al., 2013). Surface brightness in millimeter and submillimeter dust continuum emission mirrors the distribution of dust grains if they are optically thin, thus the asymmetry is a consequence of the asymmetric distribution of dust grains.

The asymmetry is considered to be the consequence of dust accumulation in regions of higher gas pressure. The hydrostatic equilibrium between the gas and the gravity of the central star means that the gas pressure has a maximum close to the star and it decreases with radius. Therefore, the concentration of dust grains in both radial and azimuthal directions might hint the existence of local gas pressure maxima which can accumulate the grains. Such regions have been gathering much attention as they may circumvent the barrier of planet formation (see Section 1.2.3) and accelerate the growth of dust grains into planetesimals and the subsequent planets. The formation mechanism of such a pressure maximum is still under debate, although the widely accepted interpretation is of the large-scale, anticyclonic vortices originate from Rossby-wave instabilities (RWI) (Lovelace et al., 1999). The RWI is induced by a radial, steep density gradient, which in turn can be a cause of dust-deficit gap opened by larger gravitating bodies or a sharp transition in the viscosity of the disk (Regály et al., 2012; Regály et al., 2013). The dust grains respond to the vortex differently based on their particle sizes, so that grains of different sizes are expected to distribute differently in the disk azimuthal direction (Baruteau and Zhu, 2016; Mittal and Chiang, 2015). The cavities observed in these non-axisymmetric disk systems usually span more than several dozens of au, which could possibly rule out the photoevaporation as the process halting the dust grains from accreting onto the star since the mechanism is capable to dissipate disk up to a radius of ~ 20 au at best (Owen, Ercolano, and Clarke, 2011).

1.2.3 Dust grains and planet formation

Dust grains are fundamental in planet formation. In the ISM or in the protoplanetary disk the dust grains are assumed follow a power-law size distribution of

$$n(a) \propto a^{-p}, \quad a_{\min} \leq a \leq a_{\max}, \quad (1.4)$$

where a is the grain radius and the distribution is parameterized by a minimum and a maximum grain size $a_{\min}$ and $a_{\max}$, as well as the exponent p . This empirical relation is first derived by Mathis, Rumpl, and Nordsieck (1977) based on the interstellar extinction; they derived $a_{\min} \sim 0.001 \mu\text{m}$, $a_{\max} \sim 0.2 \mu\text{m}$, and $p = 3.5$ for the ISM. The dust grains in the protoplanetary disks, on the other hand, are expected to encounter frequent collision due to the increased density compared to the ISM, which can lead to growth (e.g., coagulation) or destruction (e.g., fragmentation) (Beckwith, Henning, and Nakagawa, 2000; Dullemond and Dominik, 2005; Testi et al., 2014). Subsequently, the values of $a_{\min}$, $a_{\max}$, and p may be different than that of the ISM, and if coagulation is dominant grain size increases and the exponent p may become smaller (Natta et al., 2004). Once they grow larger enough, the grains sediment to the midplane where planet formation is considered to take place.

Theoretically, the planet formation is hindered by the radial drift barrier of planet formation (Weidenschilling, 1977), which is discussed here. First, we understand that the radial force balance of a parcel of gas in the disk follows

$$\frac{v_{\phi,\text{gas}}^2}{r} = \frac{GM_*}{r^2} + \frac{1}{\rho} \frac{dP}{dr}, \quad (1.5)$$

where $v_{\phi,\text{gas}}$ is the gas azimuthal velocity. The pressure gradient dP/dr on the right-hand-side is negative as the pressure near the disk mid-plane usually decreases outward. Let the mid-plane pressure varies as

$$P = P_0 \left(\frac{r}{r_0} \right)^{-n}, \quad (1.6)$$

where $P_0 = \rho_0 c_s^2$ is the pressure of the ideal gas at a fiducial radius r_0 ; the midplane density and the speed of sound are denoted by ρ_0 and c_s , respectively. The gas azimuthal velocity then becomes

$$v_{\phi,\text{gas}} = v_\phi \left(1 - n \frac{c_s^2}{v_\phi^2} \right)^{1/2}, \quad (1.7)$$

i.e., the azimuthal velocity $v_{\phi,\text{gas}}$ is slower than the Keplerian velocity v_ϕ at the same radius. Since dust grains do not directly feel the pressure and orbit at v_ϕ , the relative velocity between gas and grains results in aerodynamic drag acting on the grains; the dust grains in the disk are thus subject to friction caused by the gas. The dust grains suspended in a gas fluid orbiting around a star is characterized by the Stokes number St ,

$$\text{St} = t_s \Omega_K, \quad (1.8)$$

which is a product of the stopping time t_s and the Keplerian orbital frequency Ω_K . The stopping time describes the duration for a particle to relax to the velocity of the fluid. Micron-size particles are coupled to move with the gas as they adjust more quickly to the fluid velocity, hence $\text{St} \ll 1$. Bodies that are more than several meters in size have $\text{St} \gg 1$, and they can sustain their orbital speed at Ω_K without feeling much the head wind from the gas. On the other hand, grains of centimeter- or meter-size that have $\text{St} \sim 1$ will experience a strong radial drift towards the stars by losing their angular momentum under gas friction. For example, a grain of $\text{St} \sim 1$ at 1 au will drift to the star in about 100 yr, and if this is the case planet formation would not take place as the dust grains would be lost before they could grow to larger bodies like planetesimals of $\text{St} \gg 1$. This is the radial drift barrier of planet formation.

A scenario proposed by Kataoka et al. (2013) may circumvent the barrier and lead to the formation of planetesimals. In that scenario, dust grains grow as an aggregate via hit-and-stick coagulation of particles of size less than $1 \mu\text{m}$, known as monomers. Unlike the case of compact grains whose internal density is almost constant as they grow in size, the internal density of the aggregates decreases as their size are increasing to up to $\sim 1 \text{ cm}$. The stopping time t_s is proportional to the internal density, so a low Stokes number is obtained for centimeter-size aggregates that prevents them from rapidly drifting straight to the star.

1.3 Dust opacity

Opacity of protoplanetary disks is dominated by the dust grains; the gaps and cavities observed in the protoplanetary disks, as well as the dips in the infrared continuum in the SEDs are consequences of the decreased grains opacity at the corresponding wavelengths. This section covers the absorption mass opacity and the scattering mass opacity of the dust grains. The derived power-law size distribution in Equation (1.4) means that a mixture of grain sizes is expected in the ISM and the protoplanetary disk; however, the absorption mass opacity and the scattering mass opacity of distribution consist only of single-size grains will also be discussed, to provide a clear concept on their dependence on grain size.

1.3.1 Absorption opacity

The absorption opacity³ of dust grains depends on their size, as shown in Figure 1.6. The results are calculated by Mie theory, for compact, spherical grains of homogeneous internal density that follow a number distribution as Equation (1.4), with fix $a_{\min} = 0.01 \mu\text{m}$ and $p = 3.5$ ⁴, but varied $a_{\max}$ from $0.01 \mu\text{m}$ to 100 m . The absorption opacity of a grain of radius a , $\kappa_a(a)$, is related to the absorption coefficient $Q_a(a)$ ⁵ by

$$\kappa_a(a) = \frac{\pi a^2}{m(a)} Q_a(a). \quad (1.9)$$

To obtain a representative value for the grain distribution, κ_a ⁶, the opacity of each grain size is weighted by Equation (1.4):

$$\kappa_a = \frac{\int n(a) \kappa_a(a) da}{\int n(a) da}. \quad (1.10)$$

The figure depicts that the larger the grain size, the absorption opacity in the infrared and the visible spectrum becomes smaller, and the slope in the millimeter wavelength becomes flatter. This is because when the grains are larger than the wavelengths of incident electromagnetic waves, the interaction between them is in the geometric optics regime, and the grains will act like a gray-body to the incident light. Writing the ratio between the grain size and the wavelength as

$$x = \frac{2\pi a}{\lambda}, \quad (1.11)$$

the absorption coefficient Q_a can be approximated as

$$Q_a(a) = \begin{cases} x^\beta & \text{if } x \lesssim 1, \\ 1 & \text{if } x \gtrsim 1, \end{cases} \quad (1.12)$$

³Henceforth, I will refer absorption mass opacity, as well as scattering mass opacity, as absorption opacity and scattering opacity, respectively.

⁴Although the dynamics in protoplanetary disks is considered to be different than that in the ISM (see e.g., Birnstiel, Ormel, and Dullemond, 2011; Draine, 2006), $p = 3.5$ in the power-law size distribution is a good approximation and is widely adopted when modeling protoplanetary disks.

⁵The absorption coefficient $Q_a(a; \nu)$ and the absorption opacity $\kappa_a(a; \nu)$ are frequency dependent, so as the scattering coefficient and the scattering opacity which is discussed in the next subsection. Throughout the thesis, the frequency notation ν will be omitted.

⁶To differentiate the opacity and the absorption coefficient between the values of each grain size and the representative values for the ensemble of dust grains, the argument (a) is implicitly shown in the former, i.e., $Q_a(a)$ and $\kappa_a(a)$, to emphasize their size dependence.

where β is a measure of the absorption opacity slope in the millimeter regime (usually within 1 mm – 3 mm), and it depends mainly on the composition and the size of the dust grain. The index is approximately $\beta \approx 1.7$ in the ISM while it can be significantly smaller if the grains are larger than several microns.

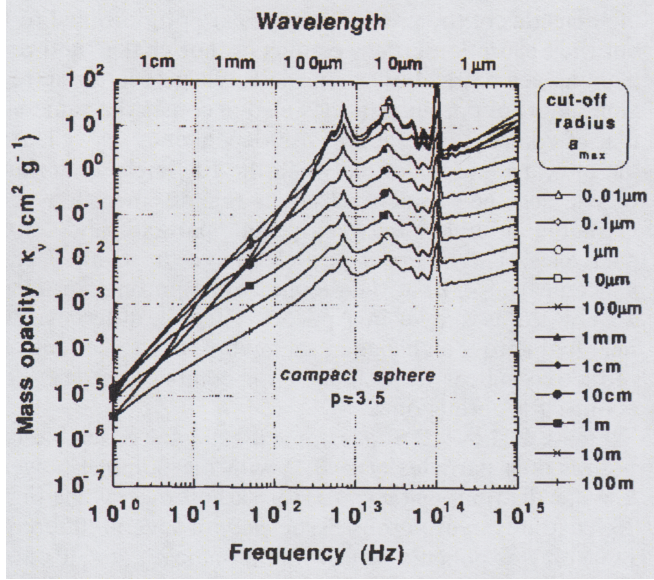


Figure 1.6: The absorption opacity (the vertical axis) of dust grains that distribute as $n(a) \propto a^{-3.5}$, with varied upper cut-off radii (i.e., maximum grain size), $a_{\max}$, plotted against the frequency or the equivalent wavelength of the incident light (the horizontal axis). Each plot is labeled with its $a_{\max}$ values. The lower cut-off radius for all the cases is $a_{\min} = 0.01 \mu\text{m}$. The grains are composed of silicate and water ice where the abundances with respect to H_2 gas are assumed to be solar. Adapted from Figure 5 in Miyake and Nakagawa (1993).

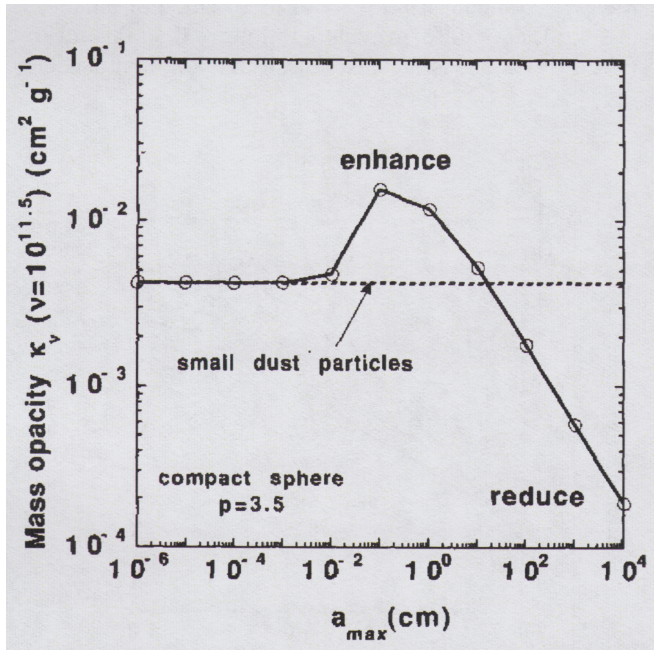


Figure 1.7: The absorption opacity at frequency $\nu = 10^{11.5} \text{ Hz}$, or $\lambda \approx 1 \text{ mm}$, plotted against the maximum grain size $a_{\max}$. The dust grains configuration is the same as that in Figure 1.6. Adapted from Figure 6 in Miyake and Nakagawa (1993).

A commonly adopted approximation for the absorption opacity at millimeter wavelengths is

$$\kappa_a = 0.1 \left(\frac{\nu}{10^{12} \text{ Hz}} \right)^\beta \text{ cm}^2 \text{ g}^{-1}, \quad (1.13)$$

which is derived from a survey of circumstellar disks in the Taurus-Auriga dark clouds region (Beckwith et al., 1990). Under Rayleigh-Jeans approximation, when dust continuum emission

is optically thin its flux at the radio wavelengths is

$$F \propto \nu^\alpha, \quad (1.14)$$

where Equation (1.13) is assumed. The observed flux slope in the SED is denoted by α and is related to the dust properties β via

$$\alpha = \beta + 2. \quad (1.15)$$

In protoplanetary disks β is typically unity or even lower as a results of grain growth, therefore the slope index α can be an indicator of pointing to the existence of processed grains larger than in the ISM. As example, when $\alpha \approx 2$ in the SEDs in Figure 1.5, the observed flux comes mainly from the stellar photophere, which indicates that small grains are depleted or have grown to larger size.

Another interesting feature of the opacity dependence on grain size is shown in Figure 1.7, where κ_a is plotted against $a_{\max}$. The calculations in Figure 1.7 are based on the same power-law size distribution as in Figure 1.6. In the sub-millimeter and millimeter wavelength, the absorption opacity is greatest when the dust size is comparable to the wavelength, i.e., when $x \sim 1$. We first understand that when the size distribution is described by Equation (1.4), for each grain size the geometrical cross section will be distributed mainly to the smaller grains if $p > 3$ while the dust mass will be dominated by the larger grains if $p < 4$. Thus, $p = 3.5$ is an intermediate case⁷. Next, by separating the plots into three regions where $x \ll 1$, $x \sim 1$, and $x \gg 1$, the results are explained as follows.

(1) $x \ll 1$, the Rayleigh regime

When the grain distribution has $a_{\max} \lesssim 10^{-2}$ cm, which is significantly smaller than the wavelength of the incident light $\lambda \approx 1$ mm, κ_a is constant. Recalling from Equation (1.12) that $Q_a = x^\beta$ and it is related to κ_a by Equation (1.9), κ_a is indeed derived to be independent of the grain size since $\beta \approx 1$ for grains mainly composed of silicate (Draine, 2006).

(2) $x \sim 1$

The transition region from Rayleigh regime to the geometric optics regime and where the absorption opacity shows a bump and reaches a peak. When $p < 4$, the mass will be dominated by the larger grains as $x \rightarrow 1$, therefore the opacity peaks as $a_{\max} \sim 1$.

(3) $x \gg 1$, the geometric optics regime

When $a_{\max} \gtrsim 10^1$ cm, the distribution has a maximum grain size which is significantly larger than the wavelength. However, if $p > 3$ the opacity will be less affected by the larger grains as the geometrical cross section of the ensemble is dominated by that of the smaller grains. In this limit $Q = 1$ as in Equation (1.12) and along with Equation (1.9) it can be seen that κ_a decreases with $a_{\max}$, which is expected as the area-to-mass ratio falls of as $\propto 1/a$. A more analytical understanding will require adding the grain mass $m(a) \propto a^3$ in the integral in both the numerator and

⁷The geometrical cross section and the grain mass are equally distributed in each size bin da/a when $p = 3$ and $p = 4$, respectively.

denominator of Equation (1.10) to obtain

$$\kappa_a = \frac{\int n(a)a^3\kappa_a(a)da}{\int n(a)a^3da}. \quad (1.10')$$

This written form follows Equation (10) of Miyake and Nakagawa (1993). The numerator is less affected by $a_{\max}$ because the opacity will be determined by smaller grains. The denominator, however, is dominated by $a_{\max}$. Consequently, $\kappa_a \propto a_{\max}^{-1/2}$.

Figure 1.7 thus shows that observation at radio wavelength is capable of probing grains of comparable size with the observation wavelength. Caution should be taken, however, when interpreting the grain size from an observation of dust continuum emission, as the bump and the peak of opacity when $x \sim 1$ may depend on the properties of the grain, i.e., be it a structural dependence (compact spherical or an aggregate, Kataoka et al., 2014), or one which is size distribution related (the value of p , Ricci et al., 2010). The grain structural difference and its consequence to the opacity will be discussed next.

Dust grains in the ISM and protoplanetary disks are often assumed to be compact, spherical solid particles, but in practice they may exist as aggregates made of monomers. The grains are porous or “fluffy” and will have shapes significantly different from a sphere. The porosity of such aggregates is defined by the volume filling factor f , in which case $f = 1$ corresponds to the case of compact, spherical grains of the radius a . The grain size can either be characterized by their gyration radii or by the characteristic radii derived from their effective dielectric functions (Bohren and Huffman, 1983). Let the aforementioned radius be a_c , a parameter that describes the aggregates is a_cf , which can be considered as the effective size radius of the aggregates if they were compact with $f = 1$. In Figure 1.8, the results of various a_cf are shown; here the opacity is calculated by the Mie theory using the effective medium approximation, or the effective medium theory (EMT)⁸, for a single-size grain, in contrary to the results in Figure 1.6 in which the power-law size distribution is accounted for. Other than the interference pattern seen in the compact case, which is due to the large refractive index of the grains when $x \sim 1$, the absorption opacity is similar regardless of the porosity, when a_cf is constant. An analytic formula obtained by Kataoka et al. (2014) is

$$Q_a = \begin{cases} Q_{a,1} & x < 1, \\ \min(Q_{a,2}, Q_{a,3}) & x > 1, \end{cases} \quad (1.16)$$

where $Q_{a,1}$ and $Q_{a,2}$ are proportional to a_cf , while $Q_{a,3} \sim 1$. The two coefficients $Q_{a,2}$ $Q_{a,3}$ accounts for the optical thickness in the grains at corresponding wavelengths, where the former is the optically thin case while the latter the optical thick case. The above equation thus indicates that Q_a are characterized by a_cf , and despite of the porosity the opacity will be identical as long as the product a_cf is the same.

The $\kappa_a(1 \text{ mm})$ dependence on structural difference is shown in Figure 1.9, which is simulated with $(a_cf)_{\min} = 0.1 \mu\text{m}$ and $p = 2$ meanwhile varying $(a_cf)_{\max}$. Although different grain size distribution is applied, the bump exists as well for the compact case $f = 1$ in Figure 1.9, similar to the results in Figure 1.7. In the aggregate form where $f < 1$, $\kappa_a(1 \text{ mm})$ does not show a bump, as the porous grains do not possess the interference pattern as shown

⁸In the EMT, a characteristic radius and an effective dielectric function for the aggregate is calculated and it is replaced with a single compact and homogenous sphere of equivalent properties.

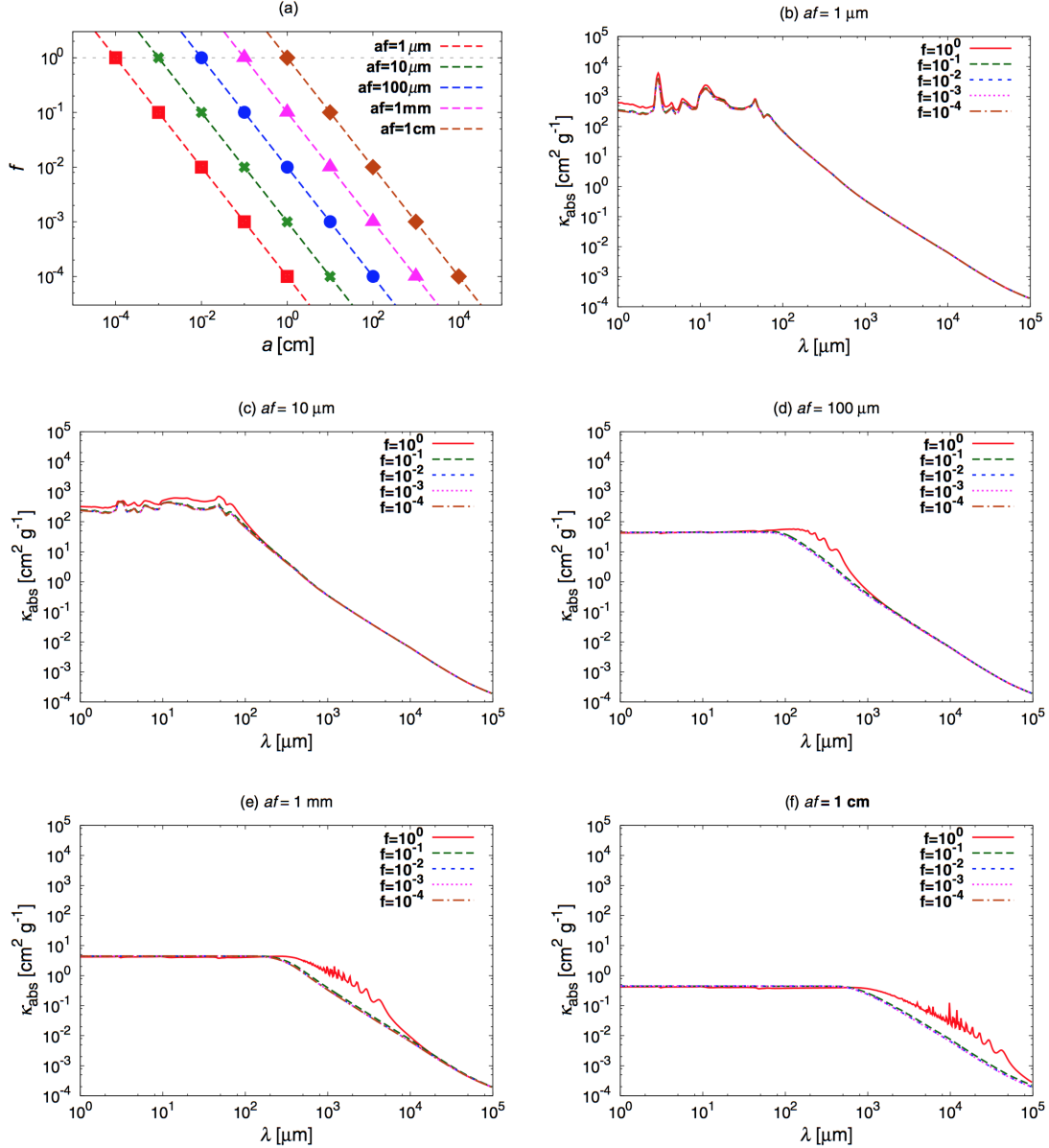


Figure 1.8: The absorption opacity per unit dust mass of various $a_c f$ plotted against the wavelength of incident light λ (in units of μm). The notation for the grain effective radius a in the figure corresponds to a_c in this literature. The opacity is calculated for a single-size grain and thus is different from the results shown in Figure 1.6, in which the power-law size distribution is accounted for. The grains are composed of silicate, organics, and ice and their mass fractional abundance are taken to be 2.64×10^{-3} , 3.53×10^{-3} , and 5.55×10^{-3} . (a): The parameter space of a_c and f . (b) – (f): The absorption opacity for different configuration of $a_c f$, where in each panel $a_c f$ is a constant. Each plot represents the different values of f , from 1 (the compact case) to 10^{-4} .

Adapted from Figure 3 in Kataoka et al. (2014).

in Figure 1.8 which gives rise to such a feature. The interference pattern thus distinguishes the compact grains from the aggregates.

Although there remains uncertainties in the structure of grains as well as the chemical composition (see, e.g., Draine, 2006), we see that the grain growth leads to the change in opacity. The grain growth is considered to be revealed in the observation as the dust-depleted

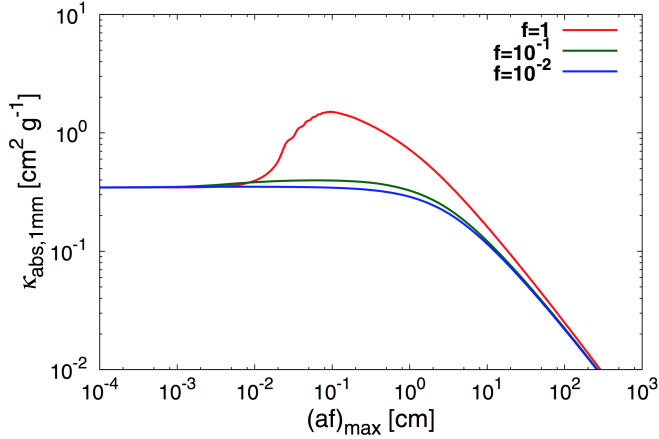


Figure 1.9: The absorption opacity at $\lambda = 1$ mm, plotted against $(a_c f)_{\max}$. The notation a in the figure corresponds to a_c in this literature. The dust grains follow the power-law size distribution as in Equation (1.4), with $(a_c f)_{\min} = 0.1 \mu\text{m}$ and $p = 2$. The three plots are the results for three various porosity f of the grains. Adapted from Figure 11(a) in Kataoka et al. (2014).

gaps or cavities, as well as the steepening flux slope at the radio wavelengths in the SEDs, just as those shown in Section 1.2.1. The observations and SEDs thus provide important clues of planet formation.

1.3.2 Scattering opacity

Compared to the absorption opacity, the scattering opacity of dust grains are relatively highly uncertain. The main reasons are, just like the case of absorption opacity, the chemical composition and the porosity of the grains. Another complication that needed to be taken care of is the light scattering angle by the grains, commonly known as the phase function. In addition, even the simulation methods used to calculate the scattering opacity can lead to different outcomes. The scattering properties of dust grains are therefore underdetermined, and most modeling works ignore dust scattering.

Some examples of scattering opacity as a result of porosity difference are shown in Figure 1.10. The grain distribution used is the single-size grain distribution exactly the same as the one in Figure 1.8. It is observed that when the wavelength is significantly larger than the parameter $a_c f$, i.e., $x \ll 1$, the opacity will be different by at least several orders depending on the porosity f . Similar to the case of the absorption coefficient, an analytic formula is obtained for scattering coefficient Q_s by Kataoka et al. (2014) as

$$Q_s = \begin{cases} Q_{s,1} & x < 1, \\ \min(Q_{s,2}, Q_{s,3}) & x > 1, \end{cases} \quad (1.17)$$

where $Q_{s,1} \propto a_c^4 f^2$, $Q_{s,2} \propto a_c^2 f^2$, and $Q_{s,3} \propto a_c f$. The last two scattering coefficients account for the optically thin and optically thick regime when $x > 1$; they are characterized by the product $a_c f$ (the square of it for $Q_{s,2}$), thus the opacity will be similar provided that a large characteristic radius is compensated by a low porosity to obtain a same value for $a_c f$. In the opposite regime where $x < 1$, the scattering coefficient does not respond as simply as $a_c f$ or any of its exponentiation, instead it will depend on a_c^2 even $a_c f$ is achieved to be the same for any configuration of a_c and f . Consequently, at the same $a_c f$ the grains of larger a_c or smaller f show a higher scattering opacity κ_s , although the absorption opacity κ_a is the same.

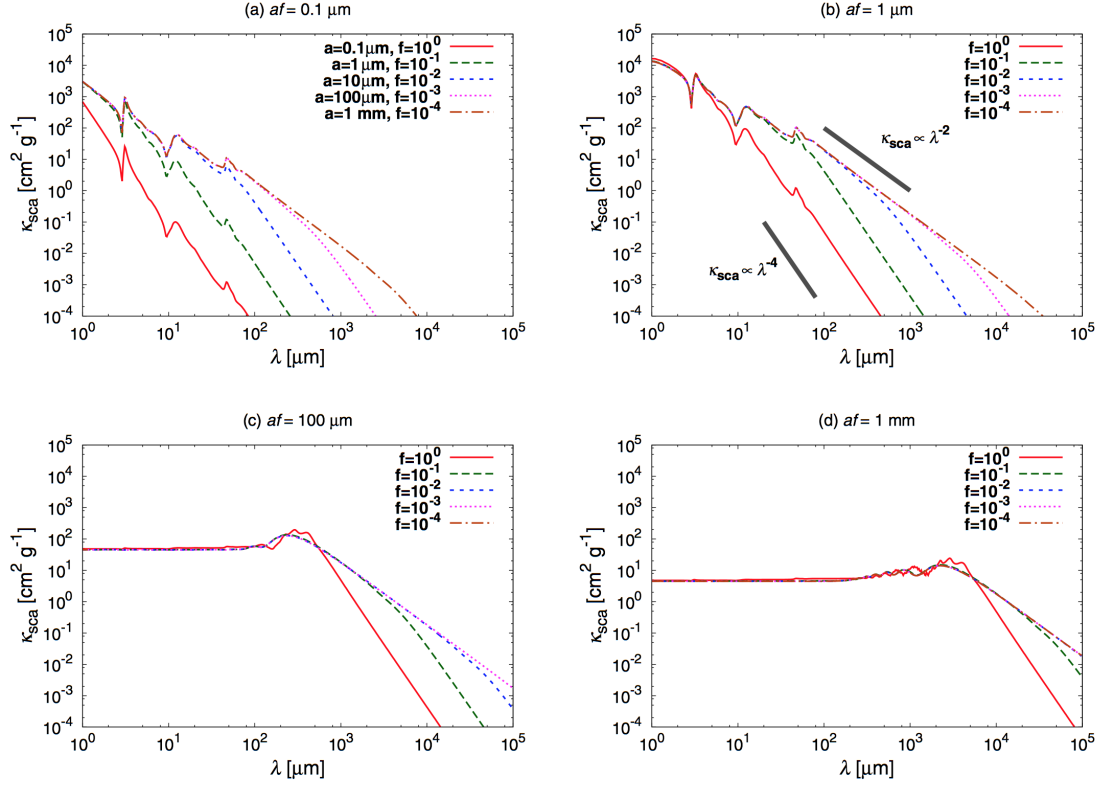


Figure 1.10: Same figure as [Figure 1.8](#), but for the scattering opacity per unit dust mass. The notations for the grain effective radius a and the scattering opacity κ_{sca} in the figure corresponds to a_c and κ_a , respectively, in this literature. From (a) to (d), the product $a_c f$ is constant at $0.1 \mu\text{m}$, $1 \mu\text{m}$, $100 \mu\text{m}$, and 1mm . Adapted from Figure 4 in [Kataoka et al. \(2014\)](#).

In the submillimeter or longer wavelengths, the scattering opacity increases as the dust grain grows, and in the simulation by [Kataoka et al. \(2014\)](#) its value is simulated to be larger than the absorption counterpart by at least an order of magnitude, as shown in [Figure 1.11](#). In particular it is highest when $x \sim 1$. While in the visible and near-infrared wavelengths scattered light of small grains is dominant, in the longer wavelengths larger grains also contribute significantly to the scattered thermal emission. Polarization has been detected in protoplanetary disks, for example in the disks around HL Tau ([Stephens et al., 2014](#)) and L1527 ([Segura-Cox et al., 2015](#)), as well as in the disk of HD 142527 ([Kataoka et al., 2016](#)). Although in most studies the magnetic field in the disk is accounted for the polarization, [Kataoka et al. \(2015\)](#) shows that the dust self-scattering might explain the polarized pattern. Despite its importance in the radio wavelengths, the scattering opacity is often omitted when modeling the dust continuum emission (see, e.g., [Isella, Carpenter, and Sargent, 2010](#); [Isella et al., 2010](#); [Pérez et al., 2012](#); [Casassus et al., 2015](#)). Under such circumstances, the disk mass might be overestimated, and the polarization pattern of the disk that originates from the dust grains self-scattering is certainly unable to be accounted for.

In [Figure 1.12](#) the phase function of scattering is shown at three different wavelengths calculated by three simulation methods, which are the T-matrix method (TMM) (see, e.g., [Mishchenko, Travis, and Mackowski, 1996](#)), the Rayleigh-Gans-Debye (RGD) theory (see, e.g., [Bohren and Huffman, 1983](#)), and the EMT. As opposed to the EMT which uses Mie

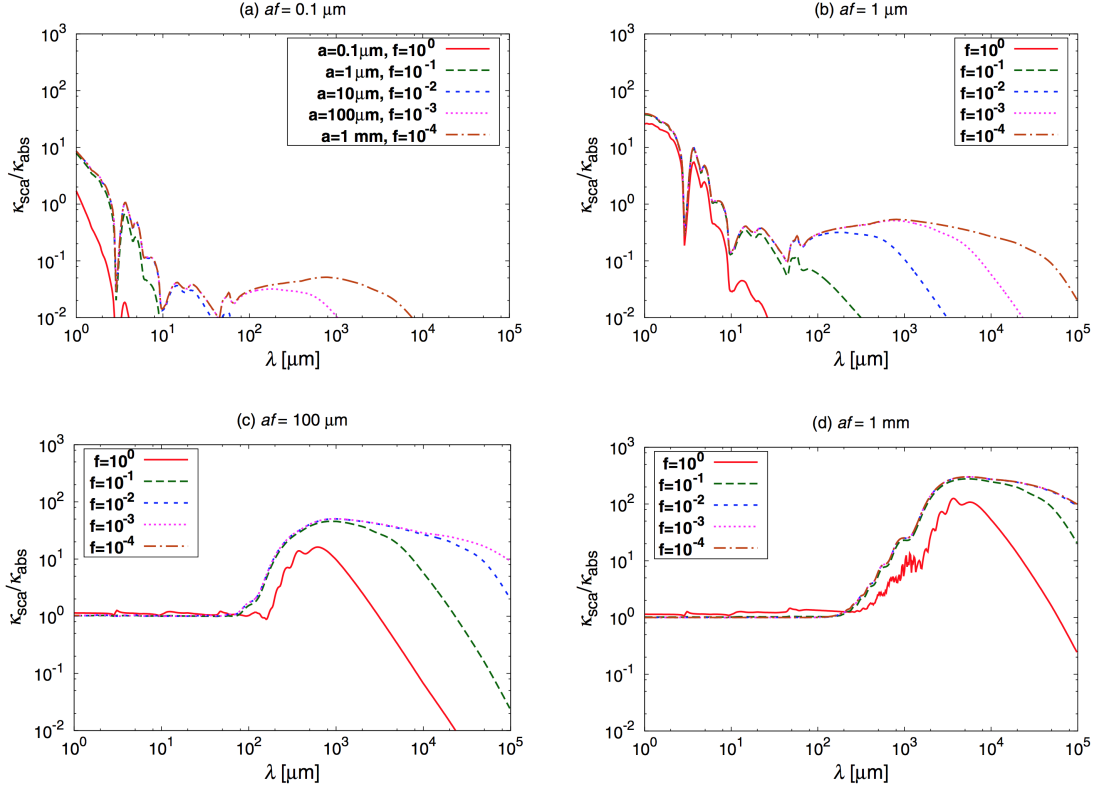


Figure 1.11: The ratio of the scattering opacity and absorption opacity plotted as a function wavelengths. The dust grain properties and size distribution are the same as the configuration used to calculate the absorption opacity in Figure 1.8 and the scattering opacity in Figure 1.10. The notations for the grain effective radius a , the absorption opacity κ_{abs} , and the scattering opacity κ_{sca} in the figure corresponds to a_c , κ_a , and κ_s respectively, in this literature. From (a) to (d), the product ac_f is constant at $0.1 \mu\text{m}$, $1 \mu\text{m}$, $100 \mu\text{m}$, and 1 mm .

Adapted from Figure 5 in Kataoka et al. (2014).

theory that requires the aggregate to be replaced with a homogenous sphere of equivalent dielectric function and refractive index, the TMM and the RGD theory take account of the particle shape, so that the optical properties of the aggregate can be obtained using the superposition principle which is crucial in determining the scattering phase function. The TMM and the RGD theory are thus the rigorous method to calculate the opacity, although the latter is valid only if the refractive index of the particle is close to the surrounding medium. From the figure, we see that the three methods derive similar results at $\lambda = 100 \mu\text{m}$, i.e., at an incident wavelength which is appreciably larger than the particle size of approximately $3.73 \mu\text{m}$. When the wavelength becomes comparable to the aggregate size, however, the EMT method deviates significantly from the rigorous simulations and underestimates the backward scattered intensity by several orders. The two rigorous methods are thus favored to simulate scattering pattern, but come at a high computational cost.

1.4 The aim of this study

As has been discussed in Section 1.3.2, when the grain size is similar to the incident wavelength at the submillimeter or millimeter regime, the scattering opacity is estimated

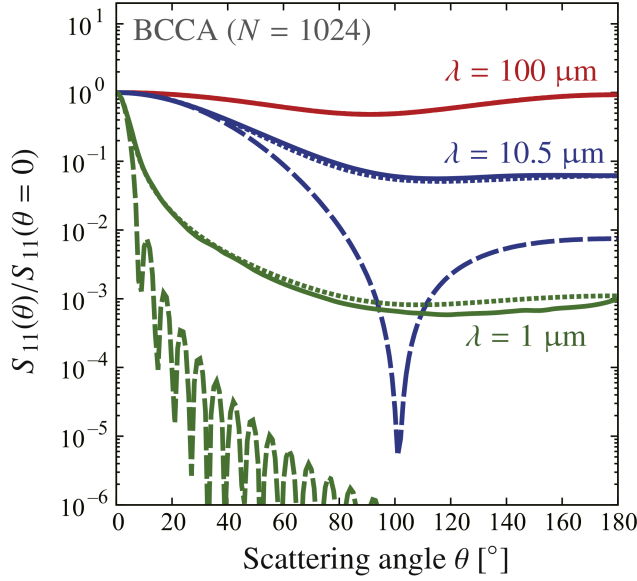


Figure 1.12: The normalized scattered intensity $S_{11}(\theta)/S_{11}(\theta = 0)$ plotted against the scattering angle θ . Scattering angle $\theta = 0^\circ$ is parallel to the propagation direction of the incident light, while $\theta = 180^\circ$ is the anti-parallel direction. The gyration radius of the aggregate, a ballistic cluster-cluster agglomerate (BCCA) consists of 1024 monomers, is approximately $3.73 \mu\text{m}$. The monomer is $0.1 \mu\text{m}$ in size radius and its chemical composition is the same as that of astronomical silicate (Draine and Lee, 1984). The solid, dotted, and dashed lines show the results calculated by the TMM, the RGD theory, and the EMT, respectively. The red, blue, and green plots denote the results in which the incident wavelengths λ are $100 \mu\text{m}$, $10.5 \mu\text{m}$, and $1 \mu\text{m}$. Adapted from Figure 4 in Tazaki et al. (2016).

to be much higher than the absorption opacity. The effects of dust self-scattering therefore should be taken into consideration when modeling the continuum emission at these long wavelengths. In addition, the improved capability of observing instruments such as ALMA which enables polarization observation with good signal-to-noise ratio will definitely urge detailed modeling of not only the polarized intensity but also the polarization pattern seen in the protoplanetary disks. The scattering nature of grains is undeniably underdetermined, and thus it must be explored via follow-up modeling of the observational data in order to examine the validity of the simulated optical and structural properties of the grains.

In this work, I model the dust continuum emission from a protoplanetary disk that surrounds a pre-main sequence, Herbig star named HD 142527, by taking not only the dust absorption opacity but its scattering opacity as well. This is important in the following ways.

- (1) The distribution of the dust surface density can be estimated with better accuracy by modeling since the observation does not resolve the outer disk.
- (2) Scattering was usually omitted in the modeling of dust continuum emission due to its ambiguous properties, but it may prove important in determining the grain size as well as the growth process of the dust grains.
- (3) Since the dust disk is lopsided and non-axisymmetric with respect to the central star HD 142527, the grain size is also expected to be varying spatially in the disk. The investigation of size distribution may provide insight to the theories of vortex formation.

This thesis is organized as follows. In Chapter 2 I introduce the target of study, HD 142547 and its circumstellar disk, and summarize the gas and dust modeling work on the target by Muto et al. (2015). The modeling method to reproduce the dust continuum emission is present in Chapter 3. The results are summarized in Chapter 4, where I will also discuss the difficulties in reproducing the observed emission at the northwest region of

the disk due to the heavy scattering. A solution, which is to reduced the scattering opacity, is proposed in [Chapter 5](#), and the difference before and after reducing the opacity will be examined. [Chapter 6](#) is reserved for the summary of this thesis.

Chapter summary

1. During the process of star formation of several or lower stellar masses, a circumstellar disk forms around the star as a result of the conservation of angular momentum. As in the interstellar medium, the disk, often called the protoplanetary disk, consists not only of gas but also a fraction of dust grains, which is considered to be the seed of planet formation.
2. Cavities and gaps, which are regions depleted of small grains, are observed in protoplanetary disks. On the spectral energy distributions, the regions are revealed as a flux deficit in a continuum of emission excess at the infrared wavelengths. These features hint at a possible planet formation in the disk.
3. Opacity in the protoplanetary disk is dominated by that of the dust grains, and it depends on the size, structure, and chemical composition of the grains.
4. Despite the simulations showing that the scattering opacity maybe dominant compared to the absorption opacity at the submillimeter or longer wavelengths, its optical properties are highly uncertain and is often omitted when modeling the observed surface brightness of protoplanetary disk.
5. This work aims at determining the dust surface distribution of the protoplanetary disk around HD 142527, by taking both the absorption opacity and the scattering opacity of dust grains.

Chapter 2

Target of study: HD 142527 disk system

2.1 Introduction

The target of this study, HD 142527, is a young Herbig star, estimated to be about 5 Myr (Fukagawa et al., 2006; Verhoeff et al., 2011) in age. The most commonly assumed spectral type is F6 – F7IIIe (van den Ancker, de Winter, and Tjin A Djie, 1998). The parallax measurement from the *Hipparcos* catalog yields a distance of $198.4^{+60.7}_{-37.6}$ pc the star. Recent works adopt a distance of 140 pc by considering its probable association with Sco OB2 in the vicinity of Lupus IV cloud (de Zeeuw et al., 1999). By using the shorter distance, the mass, radius, and the effective temperature of the star are derived to be $2.2 M_{\odot}$, $3.8 R_{\odot}$, and 6250 K (Fukagawa et al., 2006; Verhoeff et al., 2011; Mendigutía et al., 2014).

The derived accretion rate for HD 142527 depends heavily on the applied distance to the star. From the luminosity of the Br γ , Garcia Lopez et al. (2006) estimated a rate of $7 \times 10^{-8} M_{\odot} \text{ yr}^{-1}$ by assuming a distance of 200 pc. On the other hand, based on the X-shooter spectrography (Vernet et al., 2011) observations (300 nm – 2.5 μm) and by adopting a distance of 140 pc, Mendigutía et al. (2014) consider the accretion rate to be about $2 \times 10^{-7} M_{\odot} \text{ yr}^{-1}$. Mendigutía et al. (2014) reanalyzed the Br γ data from Garcia Lopez et al. (2006) to find the rate translates into about $3 \times 10^{-8} M_{\odot} \text{ yr}^{-1}$ by their methodology. Thus, they concluded that the difference is a significant one and it comes from the accretion variability of HD 142527 over a period of about five years.

Biller et al. (2012) discovered an asymmetry in the near-infrared (H -, K -, and L' -band) flux at a projected separation of about $0''.088$ from HD 142527, at a PA of approximately 133° . Their results suggest the existence of a secondary, low-mass object. The companion, named HD 142527B, was later directly imaged by Close et al. (2014) through detection of H α emission line that indicate gas accretion. A detailed analysis by Lacour et al. (2016) show that HD 142527B is about $0.13 M_{\odot}$ and 1 Myr in mass and age, respectively, with a surface temperature of 3000 K. The derived age, however, is highly uncertain due to the errors in the applied stellar evolutionary models. The companion’s orbit is considered to be coplanar with the inner disk (see Section 2.2) and its semimajor axis is derived to be $0''.14$, with a large uncertainty of a factor of two. Multi-epoch observation towards HD 142527B is thus required to ascertain its orbital elements.

2.2 Disk structure of the HD 142527 system at infrared wavelengths

Observations at various wavelengths reveal that HD 142527 harbors a transitional disk. The star and disk system in the near-infrared wavelengths is first resolved by [Fukagawa et al. \(2006\)](#). The almost face-on disk divides into two bright arcs which appears to be surrounding an inner hole that extends at least 100 au in radius. Facing each other along the east-west direction, the two arcs are different in physical structure. The eastern half spans within ~ 100 au – 400 au from the star whereas the western half spans within ~ 150 au – 490 au. A spiral arm is observed to be extending to the north from the latter. The western half is also brighter by about 2 mag in both H - and K -band unpolarized scattered light, whose cause is attributed to the anisotropy scattering of dust grains.

By fitting the SED of the HD 142527 system, which is shown in [Figure 2.1](#), [Verhoeff et al. \(2011\)](#) deduces that the disk has the following geometrically distinct components.

- (1) A geometrically flat inner disk surrounded by a halo-like structure is deduced to exist in 0.1 au – 30 au. The dust masses are estimated to be $2.5 \times 10^{-9} M_{\odot}$ and $1.3 \times 10^{-10} M_{\odot}$, for the flat disk and halo, respectively. The thin disk may be a consequence of dust grain sedimentation which is indicative of the presence of large bodies.
- (2) An extensive region devoid of small dust grains, or disk gap, in 30 au – 130 au.
- (3) A massive outer disk in 130 au – 200 au. This component contains most of the dust mass of the disk, which is estimated to be about $1.0 \times 10^{-3} M_{\odot}$. The disk is assumed to be puffed up, so that the inner wall of the disk reaches a scale height of about 60 au.

The inner wall, or the disk’s surface facing to the central star, can intercept the stellar irradiation at a large grazing angle by virtue of its large scale height. This structure then readily explains the observed large infrared excess ([Dominik et al., 2003](#)), because a large portion of the disk reprocesses much of the stellar irradiation and then emits infrared radiation into a small solid angle as seen by the observer. In addition, the thermal emission in Q -band (see also [Fujiwara et al., 2006](#)) show that the outer disk is brighter on the eastern side, which is a contrasting case to the aforementioned brightness asymmetry in unpolarized scattered light. The results thus indicate that the disk is inclined, by approximately 30° , along the northeast-southwest direction where the northeastern side is further away from us.

Later observations at the near-infrared wavelengths are consistent with the previous two studies ([Rameau et al., 2012](#); [Canovas et al., 2013](#)). In particular, by using polarimetric differential imaging technique, [Avenhaus et al. \(2014\)](#) obtained high resolution images in H - and K_s -band that reveal six spiral arms in the outer disk. They also reported that, although the eastern half is darker than the opposite half in unpolarized scattered light at the near-infrared, both of them are similar in terms of polarized intensity; the eastern side is thus higher in polarization fraction. These observed features can be well explained by a combined effect of the disk’s inclination and the properties of dust grain (e.g., porosity or composition) which determines the scattering angle (see e.g., [Perrin et al., 2009](#)). No inner disk is detected

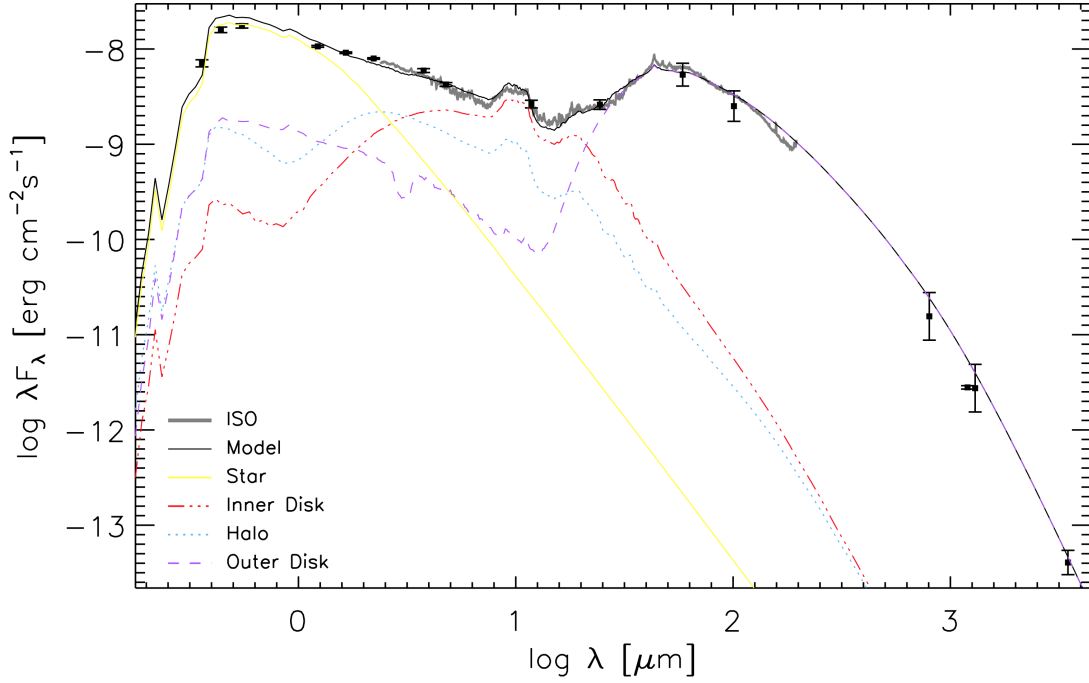


Figure 2.1: The spectral energy distribution of the HD 142527 disk system. The observational data from various literature is plotted with squares with error bars (Beichman et al., 1988; Malfait, Bogaert, and Waelkens, 1998; Walker and Butner, 1995; Verhoeff et al., 2011), and the one taken by Infrared Space Observatory is plotted in solid gray line (Meeus et al., 2001; Dominik et al., 2003). The model total flux is plotted as the black solid lines, while its contributing constituents are plotted in different line styles and colors, each labeled in the lower left corner.

Adapted from Figure 14 in Verhoeff et al. (2011).

at radii down to $0''.1$, or equivalently about 15 au at HD 142527, which may suggest that the disk is smaller than predicted.

Another intriguing feature of the HD 142527 system seen in the near-infrared images is the two intensity nulls found in the north and the south of the disk. According to Marino, Perez, and Casassus (2015), the occurrence is thought to be the consequence of the central star shadowed by the inner disk. Their model predicts that the disk is approximately 10 au in radius and is inclined by about 70° relative to the outer disk, with its projected major axis oriented at a PA of -8° .

2.3 Disk structures of the HD 142527 at radio wavelengths

Here I cover the observational results towards the HD 142527 disk system at radio wavelengths, by introducing the data obtained with Atacama Large Millimeter/submillimeter Array (ALMA). Similar to the images at the infrared, the gap and the outer disk are also seen in the submillimeter dust continuum emission (Casassus et al., 2013; Fukagawa et al., 2013), although the longer wavelengths probe emitting dust grains nearer to the disk's midplane since they are less opaque. The submillimeter emission from the outer disk, however, does not show any signs of spiral structures; instead, it is strongly azimuthal-asymmetric, the appearance of which can be best resembled by a horseshoe or a crescent. Based on the ALMA Cycle 0 results reported by Fukagawa et al. (2013), the intensity maximum of the

disk is located at a PA of 30° and is about $1''.0$ (140 au) away from the central star, with a flux density as high as $213 \text{ mJy beam}^{-1}$. From there, the horseshoe-like ridge that delineates the peak emission at each PA meets a minimum at a PA of 220° . This intensity minimum is located at a projected distance of $1''.3$ (182 au) and shows a value of 7 mJy beam^{-1} , 30 times lower than the intensity maximum. Unless the temperature distribution differs significantly, in which case is highly unlikely, the northern region of the disk is considered to be more dust-concentrated than the south. The gap within the horseshoe structure is approximately 150 au in radius, and corroborates with the infrared images that the region is depleted of small dust grains. The inner disk, although spatially unresolved by the synthesized beam, is significantly detected at the position of the star, whose existence is thus indicated as well at the radio wavelengths.

The gas around HD 142527, on the other hand, distributes differently from the dust. The integrated intensities of $^{13}\text{CO } J = 3 - 2$ and $\text{C}^{18}\text{O } J = 3 - 2$ fluctuate less than a factor of two in the PA , and they are more axisymmetric compared to the dust continuum. In addition, the gas exists in the dust-depleted gap. The velocity fields, or the first moments, of the two emission lines are consistent with a circular Keplerian motion around the central star. Taking the mass of the star to be $2.2 \pm 0.3 M_\odot$, [Fukagawa et al. \(2013\)](#) derived the inclination of the disk to be $26.9^{+2.2}_{-1.8}$. From the observational results of the $\text{HCO}^+ J = 4 - 3$ emission, [Casassus et al. \(2013\)](#) reported that there are two gap-crossing filaments that connect the outer disk to the inner disk. With each extending eastward and westward from the star, the two filaments are considered to be funneling material from the outer reservoir to the inner disk. The flow rate is estimated to be in the range of $7 \times 10^{-9} M_\odot \text{ yr}^{-1}$ to $2 \times 10^{-7} M_\odot \text{ yr}^{-1}$, which can be interpreted as the supply rate of material to the inner disk so that accretion onto the star can be maintained at its present value.

Polarization observation of the protoplanetary disk around HD 142527 has been carried out by [Kataoka et al. \(2016\)](#), with ALMA during its Cycle 4 phase. The disk is not axisymmetric in terms of polarized intensity: it shows a peak intensity in the eastern region and has two substructures in the northeast and northwest regions. The polarization vectors are aligned radially in the disk, with the exception of those in the substructures; the vectors, instead of pointing towards the star, are rotated by 90° . Another intriguing feature is of the polarization fraction. Defined as the ratio of the polarized intensity to the total intensity, the fraction shows an anti-correlation to the distribution of dust continuum emission, where the darkest region in the total intensity is the highest in the polarization fraction. In particular, the southwest region reaches a fraction as high as about 14%. [Kataoka et al. \(2016\)](#) discussed the morphology of the polarization on the basis of grain alignment with magnetic field and self-scattering by dust grains. Within the framework of the former, the magnetic field configuration is expected to be perpendicular to the polarization vectors, in which case the field would be poloidal in the two substructures instead of being toroidal like the most region of the disk. Therefore, unless there is a mechanism to change the magnetic field, in the substructures the grain alignment might be different from that invoked by magnetic field. The self-scattering scenario, on the other hand, can successfully explain the orientation of the polarization vectors based on the dust optical depth, i.e., the dust distribution in the disk ([Kataoka et al., 2015](#)), but the model polarization fraction turns out to be much lower than the observed. The reason is most likely to be coming from both the size and the spatial distributions of dust grains in the disk; it is predicted that the trailing and leading sides of

the dust-trapping vortex, which is thought to coincide with the peak in dust continuum emission, could have different distributions (Zhu and Baruteau, 2016; Baruteau and Zhu, 2016). The dust trap model is reinforced by observations by Australia Telescope Compact Array (ATCA) at 34 GHz, which reveals a large clump indicative of the presence of centimeter-size dust grains in the northern region of the disk Casassus et al. (2015).

2.4 A modeling work by Muto et al. (2015)

This section summarizes the results obtained by Muto et al. (2015) who carried out a detailed modeling to reproduce the dust and the gas distribution of the disk around HD 142527. Before getting into the results, the observational data and the data reduction in the work will be introduced. In this thesis, I use the same observational data of dust continuum emission reduced by Muto et al. (2015).

2.4.1 Observational data

Table 2.1: The synthesized beam and noise level of the ALMA Cycle 0 observation towards HD 142527.

Observation	Beam size (FWHM)	<i>PA</i> orientation	RMS noise (mJy beam ⁻¹)
Dust continuum (336 GHz)	0''.47 × 0''.40	59°.9	0.13
¹³ CO (<i>J</i> = 3 – 2)	0''.50 × 0''.42	57°.4	†6.1
C ¹⁸ O (<i>J</i> = 3 – 2)	0''.50 × 0''.42	60°.6	†8.3

† In the line observations the rms noise level is per channel, which is 0.12 km s⁻¹ in width.

Muto et al. (2015) use the continuum data of HD 142527 taken by ALMA over the period from 2012 June to August (ADS/JAO.ALMA#2011.0.00318.S). The data is the same as that used by Fukagawa et al. (2013), which was mentioned in Section 2.3. The observation period was during the ALMA Cycle 0, where six scheduling blocks were carried out by using the Extended Array Configuration consisting of 20 to 26 12 m antennas, forming a maximum baseline of about 480 m. The correlator was configured to store dual polarizations in four separate spectral windows. The central frequencies for the windows were 330.588, 329.331, 342.883, and 342.400 GHz, to target the molecular lines of ¹³CO (*J* = 3 – 2) and C¹⁸O (*J* = 3 – 2). Each window had a 469 MHz bandwidth over 3840 channels, thus resulting in a channel spacing of 122 kHz, or 0.12 km s⁻¹ in velocity at these bandwidths. The effective spectral resolution for the line observations was reduced to ~ 0.2 km s⁻¹ after Hanning smoothing. On the other hand, the continuum data at 336 GHz, or $\lambda_{\text{obs}} = 890 \mu\text{m}$ is obtained by aggregating all the line-free channels in the spectral windows that led to a 1.8 GHz bandwidth. The on-source integration time was three hours after flagging aberrant data.

Calibration and data reduction are made with the Common Astronomy Software Applications (CASA) package version 3.4. After calibrating the bandpass, gain, and flux scaling, the corrected visibilities were imaged and deconvolved by using the CLEAN algorithm (Högbom, 1974) with the Briggs weighting with a robust parameter of 0.5, and followed next

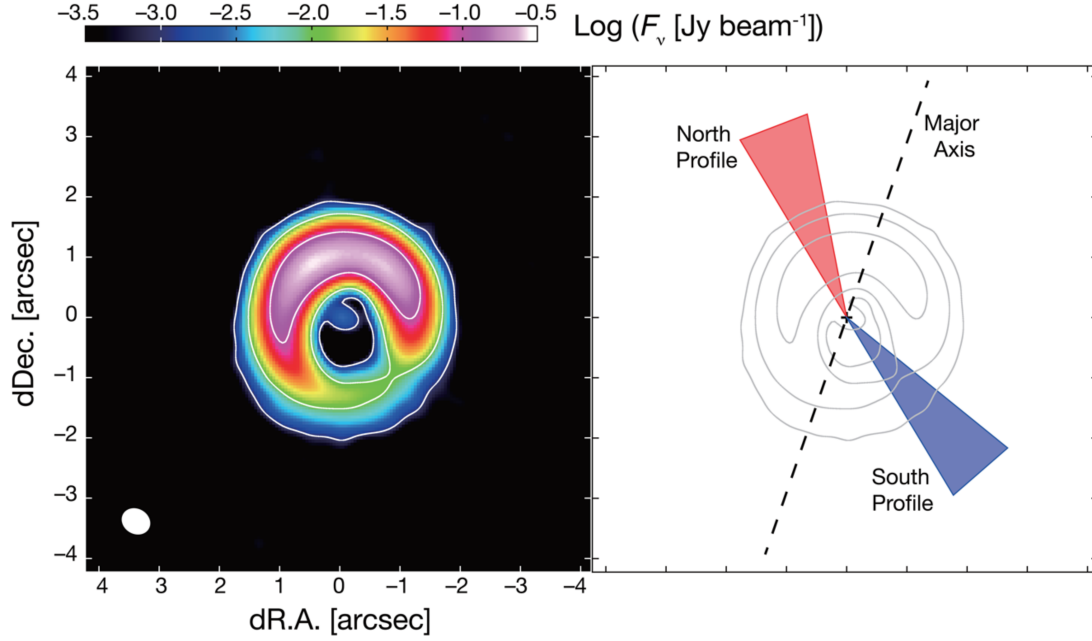


Figure 2.2: **Left:** Map of the dust continuum emission at 336 GHz, in units of Jy beam^{-1} . The synthesized beam, $0''.47 \times 0''.40$ in full width at half maximum (FWHM) and major axis oriented along $PA = 59^\circ.9$, is indicated by the white ellipse in the bottom left. The root-mean-square noise level, σ_{noise} , in the image is $0.13 \text{ mJy beam}^{-1}$, and the white contours correspond to 1, 10, and 100 mJy beam^{-1} . **Right:** Only the contours of the continuum emission from the left panel is shown. The dashed line indicates the position angle of the disk major axis, which is $PA \approx 161^\circ$. The red and the blue hatches cover $PA = 11^\circ - 31^\circ$ and $PA = 211^\circ - 231^\circ$, respectively. Intensities in the hatches are azimuthally averaged over the 20° -sector to obtain the north and the south profiles, which are shown in Figure 2.5.

Adapted from Figure 1 in Muto et al. (2015).

by the self-calibration. In the final CLEANing, Fukagawa et al. (2013) applied the Uniform weighting, in contrast to Muto et al. (2015) which applied the Briggs with a robust parameter of 0.5 to best recover the weak and extended components of the emission. components of the dust emission. The full width at half maximum (FWHM) of the synthesized beam and the position angle PA of the beam major axis are listed in Table 2.1. In the continuum observation, the beam size interprets to a physical scale length of about 60 au at the distance of HD 142527.

The map of continuum emission is plotted in Figure 2.2, while those of the rotational lines are in Figure 2.3 and Figure 2.4. Comparing the dust continuum emission to those of the molecular lines, it is evident that the dust and the gas distribute differently in the disk. Also, while the gas is relatively axisymmetric with respect to the star, the dust is not; the continuum emission peaks at the northern region of the disk, and is brighter than the southern half by about a factor of 30, as discussed in Section 2.3. From the doppler effect in the gas kinematics, we see that the disk is rotating clock-wise from our line of sight.

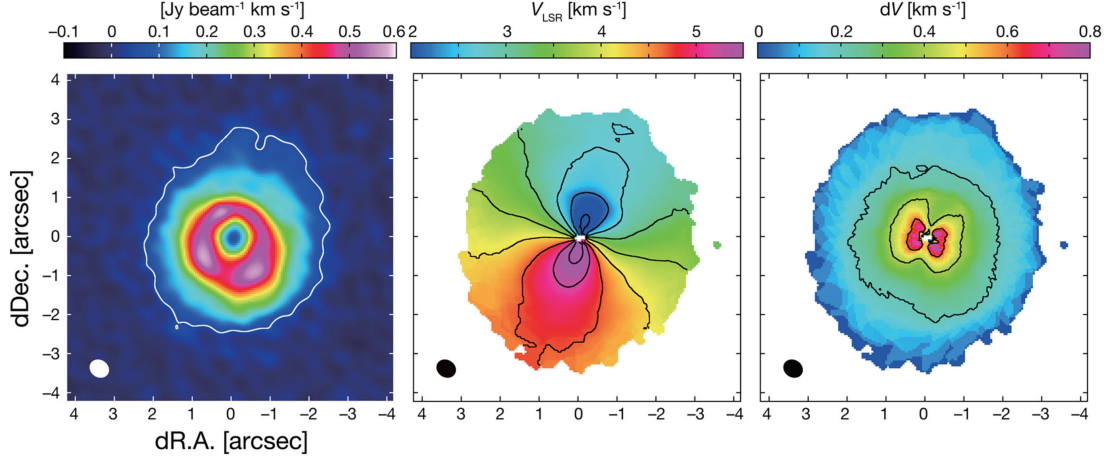


Figure 2.3: The gas kinematics in the disk around HD 142527 traced by ^{13}CO ($J = 3 - 2$). The abscissa and the ordinate are common for the figures; the former is the right ascension offset while the latter is the declination offset, relative to the star HD 142527. The ellipse in the left bottom in each panel denotes the synthesized beam, which is $0''.50 \times 0''.42$ in FWHM with its major axis align in $PA = 57^\circ.4$. **Left:** Moment 0 of the line emission (in units of $\text{Jy beam}^{-1} \text{ km s}^{-1}$), integrated over the velocity range $v_{\text{LSR}} = 0.40 \text{ km s}^{-1} - 7.00 \text{ km s}^{-1}$. The white contour shows the $5\sigma_{\text{noise}} = 48 \text{ mJy beam}^{-1} \text{ km s}^{-1}$ level. **Center:** Moment 1 map showing the velocity distribution of the gas. The relatively straight contour in $PA \approx 71^\circ$ is the systemic velocity of the system at $v_{\text{LSR}} = 3.7 \text{ km s}^{-1}$. The contours are drawn successively with a 0.5 km s^{-1} spacing from this systemic velocity. **Right:** Moment 2 map showing the dispersion in the velocity distribution. The contours start at 0.2 km s^{-1} with a 0.2 km s^{-1} increment.

Adapted from Figure 3 in Muto et al. (2015).

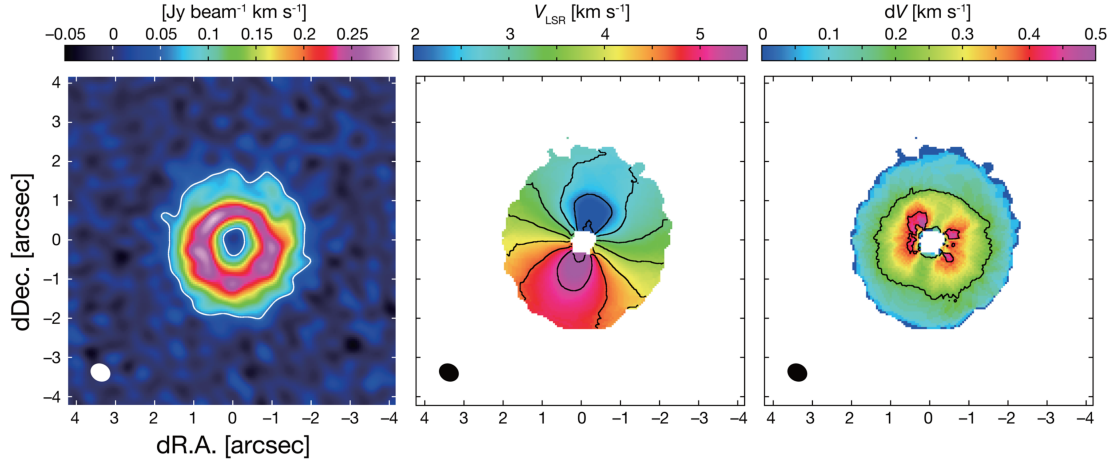


Figure 2.4: Similar to Figure 2.3, for the case of C^{18}O ($J = 3 - 2$). The ellipse in the left bottom in each panel denotes the synthesized beam; $0''.50 \times 0''.42$ in FWHM, major axis align in $PA = 60^\circ.6$. **Left:** Moment 0 of the line emission integrated over $v_{\text{LSR}} = 1.00 \text{ km s}^{-1} - 6.40 \text{ km s}^{-1}$. The white contour shows the $5\sigma_{\text{noise}} = 55 \text{ mJy beam}^{-1} \text{ km s}^{-1}$ level. **Center:** Moment 1 map. The systemic velocity of the system is $v_{\text{LSR}} = 3.7 \text{ km s}^{-1}$ as can be deduced from the relatively straight contour along $PA \approx 71^\circ$. The contours are drawn successively with a 0.5 km s^{-1} spacing from this systemic velocity. **Right:** Moment 2 map. The contours at 0.2 km s^{-1} and 0.4 km s^{-1} are shown.

Adapted from Figure 4 in Muto et al. (2015).

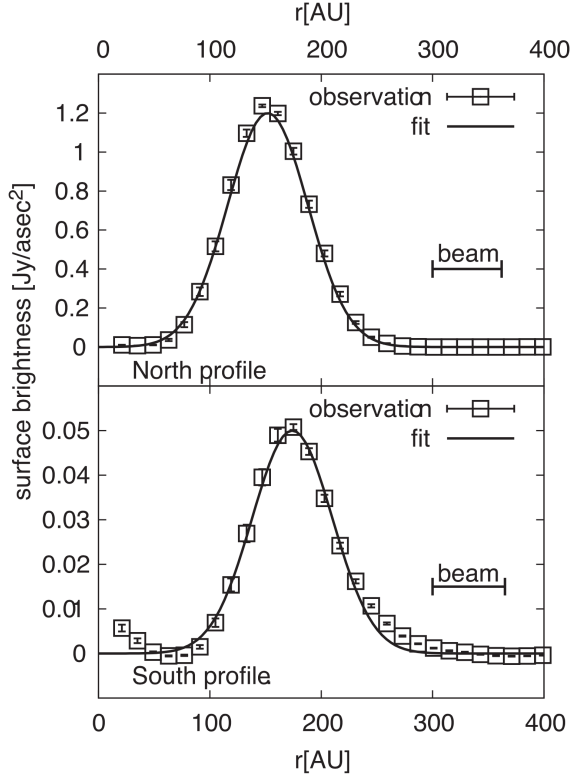


Figure 2.5: The radial intensity profile of the north (top panel) and the south (bottom panel) sectors. The abscissa is the radial distance from the star (in units au) and the ordinate is the intensity (in units Jy asec^{-2}). The observational data is indicated by the squares with the error bars showing the standard deviation after averaging over 20° in PA . The best-fit Gaussian function is indicated by the solid line. Adapted from Figure 2 in [Muto et al. \(2015\)](#).

Table 2.2: Optimized parameters for the dust surface density distribution.

Parameter	North	South
$\Sigma_{d,0}$ (g cm^{-2})	0.6	8.45×10^{-3}
$r_{d,0}$ (au)	173	196
$w_{d,0}$ (au)	27	34

Adapted and modified from Table 2 of [Muto et al. \(2015\)](#).

2.4.2 Modeling results

Making use of the continuum emission data at $\lambda_{\text{obs}} = 890 \mu\text{m}$, as well as the ^{13}CO ($J = 3-2$) and the C^{18}O ($J = 3-2$) line emission data obtained with ALMA in Cycle 0, [Muto et al. \(2015\)](#) focused on two sectors of the disk: $PA = 11^\circ - 31^\circ$ and $PA = 211^\circ - 231^\circ$, the brightest and the faintest sectors, in the dust continuum emission, respectively, as depicted in the right panel of [Figure 2.2](#). The sectors are referred to as the north sector and the south sector in their literature, and within each sector the radial profiles of the continuum emission, as well as the moment 0 and the moment 1 of the two CO lines are created; the profiles of the continuum emission are shown in [Figure 2.5](#) while of the gas are in [Figure 2.6](#). These profiles are the subject which [Muto et al. \(2015\)](#) aim at reproducing with disk models. They applied a power-law distribution for the dust grain size as in [Equation \(1.4\)](#) where $p = 3.5$ and the maximum radius of the grains is $a_{\text{max}} = 1 \text{ mm}$, i.e., the dust grains are considered to have grown significantly from those in the interstellar medium whose canonical value is $1 \mu\text{m}$

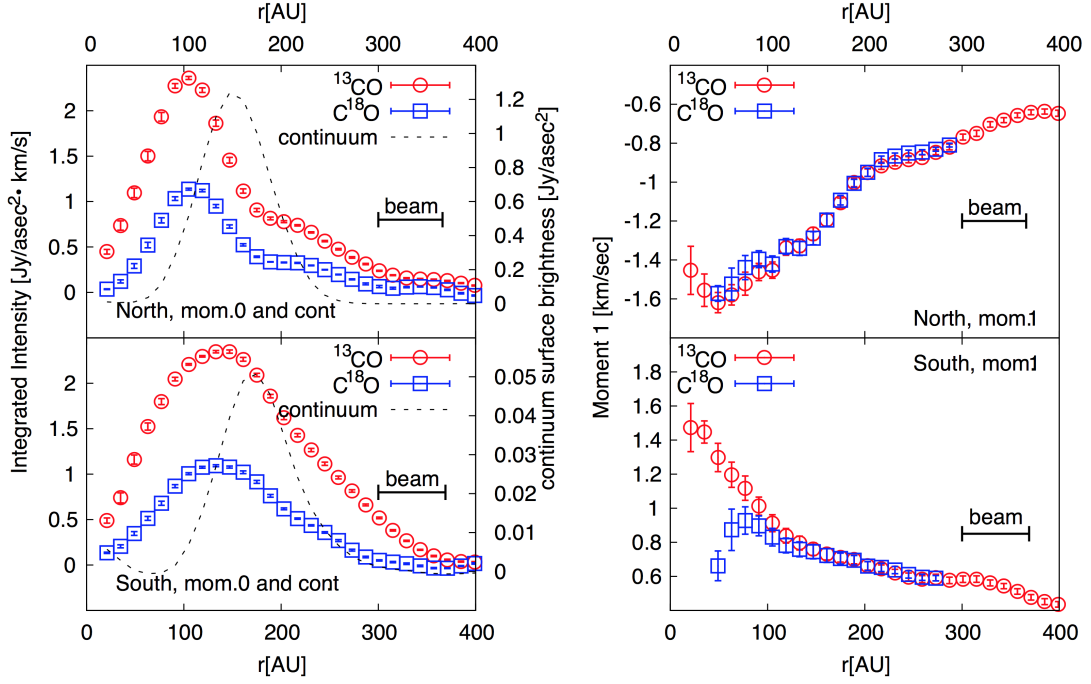


Figure 2.6: **Left:** The observed moment 0 radial profiles of ^{13}CO ($J = 3 - 2$) and C^{18}O ($J = 3 - 2$), plotted as red circles and blue circles, respectively. The continuum profiles are overplotted as dashed lines, intensity of which is indicated in the right axis. The top panel is the profiles of the north sector while the bottom panel is of the south sector. **Right:** The moment 1 profiles for the two sectors, after subtracting the systemic velocity $v_{\text{LSR}} = 3.7 \text{ km s}^{-1}$. The error bars in all panels are the standard deviation after averaging over the 20° -sector.

Adapted from Figure 5 in [Muto et al. \(2015\)](#).

or less. The scattering opacity is also considered in their work. An axisymmetric disk model is used to reproduce the intensity profiles of the sectors.

Firstly, on the derived surface density distribution of the dust grains. Since the continuum emission profiles in the north and the south sectors can be well fitted by a Gaussian function, in their model they assumed a similar distribution for the dust surface density:

$$\Sigma_d(r) = \Sigma_{d,0} \exp \left[- \left(\frac{r - r_{d,0}}{w_{d,0}} \right)^2 \right]. \quad (2.1)$$

The dust surface density in the radial direction, $\Sigma_d(r)$, is parametrized by $\Sigma_{d,0}$, $w_{d,0}$, and $r_{d,0}$, which are the peak surface density, the width of the ring, and the radial position of the peak surface density, respectively. The best-fit parameters for the north and the south profiles are listed in [Table 2.2](#). The radial width w_d of the ring translate into a FWHM of approximately 50 au for both profiles. The dust grains in the north concentrate at a radii of about 170 au from the star, as opposed to those in the south which are located further at about 200 au. The dust surface density in the north is derived to be about 0.6 g cm^{-2} , whereas in the south it is about 0.008 g cm^{-2} . They are different by a factor of about 70 and is most readily explained by the highly azimuthal-asymmetric structure of the observed continuum emission. The contrast in the observed intensity (or surface brightness) between the two sectors, on the other hand, is only about 30. Thus, it is concluded that the northern

Table 2.3: Optimized parameters for the gas surface density distribution.

Parameter	North	South
$\Sigma_{g,0}$ (g cm ⁻²)	0.845	0.2325
r_{in} (au)	110	100
r_{out} (au)	250	250
f_{in}	0.125	0.125
f_{out}	0.01	0.1

Adapted and modified from Table 6 of [Muto et al. \(2015\)](#).

region of the disk is most likely to be optically thick that the surface density does not raise the intensity linearly. Uncertainties in the properties of dust grains, especially their opacities, still remain and therefore the results are not strictly constrained.

The derived gas distribution is different from that of the dust. The gas is more radially extended than the dust and its distribution is described as

$$\Sigma_g(r) = \begin{cases} f_{\text{in}}\sigma_g(r_{\text{in}}) \left(\frac{r}{r_{\text{in}}}\right) & (r < r_{\text{in}}), \\ \sigma_g(r) & (r_{\text{in}} < r < r_{\text{out}}), \\ f_{\text{out}}\sigma_g(r_{\text{out}}) & (r > r_{\text{out}}), \end{cases}$$

where $\sigma_g(r)$ is given as

$$\sigma_g(r) = \Sigma_{g,0} \left(\frac{r}{200 \text{ au}}\right)^{-1}. \quad (2.2)$$

The parameters $\Sigma_{g,0}$, r_{in} , and r_{out} denote the peak amount of gas surface density, the inner cutoff radius, and the outer cutoff radius of the gas in the disk, respectively. The amount of gas within r_{in} and beyond r_{out} are control by the parameters f_{in} and f_{out} . The optimized parameters are tabulated in [Table 2.3](#). Based on the modeling of moment 0, moment 1, and moment 2 of the ¹³CO ($J = 3 - 2$) and the C¹⁸O ($J = 3 - 2$) lines, [Muto et al. \(2015\)](#) concluded that they have to include a little amount of gas within the dust-depleted gap as well as in the region greater than 250 au in order to reproduce the gas kinematics. The north sector is only about three times as more gas than the south sector, difference thereof is much less significant than the one seen in the dust distribution.

2.4.3 Summary

[Figure 2.7](#) summarizes the surface density derived by [Muto et al. \(2015\)](#), from which we can see that the dust accumulates in the region of high gas concentration. [Muto et al. \(2015\)](#) concluded that the gas-to-dust ratio not only varies radially but it may also differs significantly in the azimuthal direction. At the radius of the peak dust surface density, $r_{d,0}$, the ratio is ~ 3 and ~ 30 for the north and the south sectors, respectively. The global distribution of gas and dust as speculated by the authors is illustrated in [Figure 2.8](#). The disk is not constant in gas-to-dust ratio, and its value is expected to be in the range of $\sim 10 - 40$ within 400 au of the disk. These results indicate the radial drift of dust grains towards the star as well as the accumulation of dust grains in the northern region of the disk.

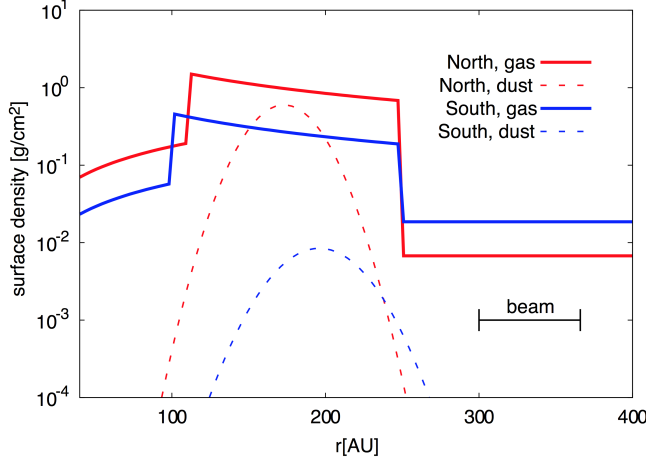


Figure 2.7: The derived gas and dust surface density distribution in the radial direction by Muto et al. (2015). The results for the north and the south sectors are indicated by the red and blue plots, respectively. The gas and the dust surface density are plotted in solid and dashed lines, respectively.

Adapted and modified from Figure 26 of Muto et al. (2015)

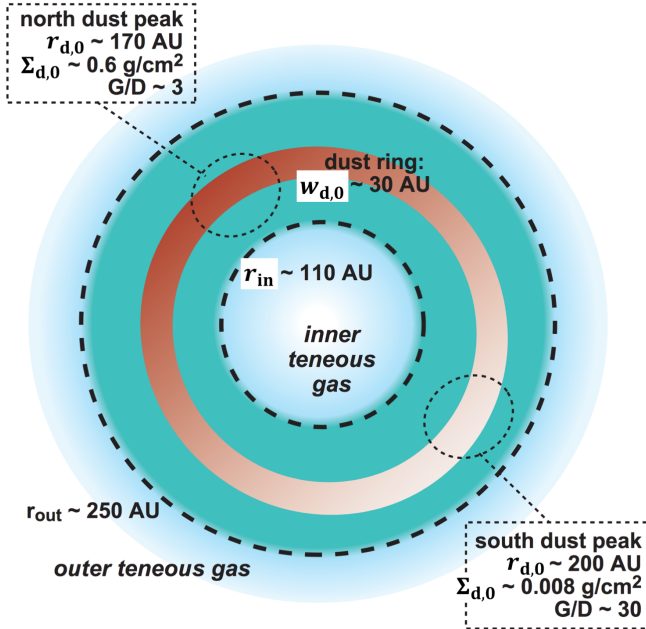


Figure 2.8: Based on their modeling work which includes only the north ($PA = 11^\circ - 31^\circ$) and the south ($PA = 11^\circ - 31^\circ$) sectors, Muto et al. (2015) speculated the global distribution of gas and dust in the disk around HD 142527, as shown in the figure. The dust peak surface density and its radial location are denoted by $\Sigma_{d,0}$ and $r_{d,0}$, respectively. The dust grains concentrate in region indicated by the brownish ring; the darker the color, the higher the surface density. The gas distributes mainly between ~ 100 au and ~ 250 au, and its surface density in this region is in proportion to the inverse of the radial distance, i.e., $\propto r^{-1}$. Tenuous gas remains outside of this region, indicated by the blueish portions in the figure. The gas-to-dust ratio (written as G/D in the figure) is expected to vary not only radially but also azimuthally in the disk.

Adapted and modified from Figure 31 of Muto et al. (2015)

Chapter summary

1. The target of study, HD 142527 is a Herbig star of age ~ 5 Myr and is located at about 140 pc. Recent observations found that the star has a companion of mass $\sim 0.13 M_{\odot}$.
2. The protoplanetary disk around HD 142527 is revealed to be non-axisymmetric and several spiral arms are observed. In the submillimeter and millimeter wavelengths, the disk is bright in the northern region, faint in the southern region, implying dust concentration in the former.
3. Polarization is also observed. The polarized pattern can be explained by the scenario of dust self-scattering.
4. Modeling work by [Muto et al. \(2015\)](#) at the brightest (north) and the faintest (south) sectors of the disk show that the dust grains accumulate at the gas-concentrated region. Their results also hint at a significant low gas-to-dust ratio in the disk compared to the canonical value of 100 in the ISM. The ratio is also speculated to be varying azimuthally.

Chapter 3

Modeling the dust distribution of the disk around HD 142527

In contrast to the modeling work carried out by [Muto et al. \(2015\)](#) which have covered gas and dust modeling in two sectors of the disk around HD 142526, I aim at deriving the dust surface density distribution of the disk in all azimuth direction. To this end, I use the disk image of HD 142527 at $\lambda = 890 \mu\text{m}$ continuum emission CLEANed by [Muto et al. \(2015\)](#); the observational data and reduction are summarized in [Section 2.4.1](#). By using a two-dimensional, axisymmetric disk model, a parameter search is performed individually to all the azimuthal sectors of the disk to obtain best-fit values that can reproduce the observed peak intensity and its location radius, as well as the radial width of the intensity profile. I use the same modeling procedure as the one applied by [Muto et al. \(2015\)](#), with the only difference being the criteria setting in the modeling that will be discussed in [Section 3.3.4](#). In this chapter, the groundwork of the modeling is first introduced, followed by the procedure in searching the best-fit values for the dust distribution.

3.1 Groundwork

As the groundwork, radial intensity profiles of the dust continuum emission are created from the reduced disk image shown in [Figure 3.1](#), where the projected image is divided into 18 azimuthal sectors, with each sector has a 20° span and a radial bin width of 14 au. This can be visualized as a polar grid imprinted on the continuum image; the star is located at the origin of the grid, while the polar axis is aligned along the disk major axis at $PA = 161^\circ$. Within each grid, the intensities are averaged to obtain a discrete, radial profile for every sector. The profiles obtained can be well approximated by a Gaussian function, namely

$$I_{\text{obs}}^*(r_{\text{obs}}^*) = I_{0,\text{obs}}^* \exp \left[- \left(\frac{r_{\text{obs}}^* - r_{0,\text{obs}}^*}{w_{0,\text{obs}}^*} \right)^2 \right], \quad (3.1)$$

where r_{obs}^* denotes the projected radius from the star, $I_{0,\text{obs}}^*$ ¹ the peak intensity at $r_{0,\text{obs}}^*$, and $w_{0,\text{obs}}^*$ the projected width of the radial profile. The results of a Gaussian fit are listed

¹Specific intensity, or simply intensity, is usually denoted by I_ν . The subscript ν signifies that intensity is a quantity of spectral energy density, per unit time, unit area, and unit solid angle. Throughout the paper, unless indicated the subscript signifying spectral density will be omitted for convenience.

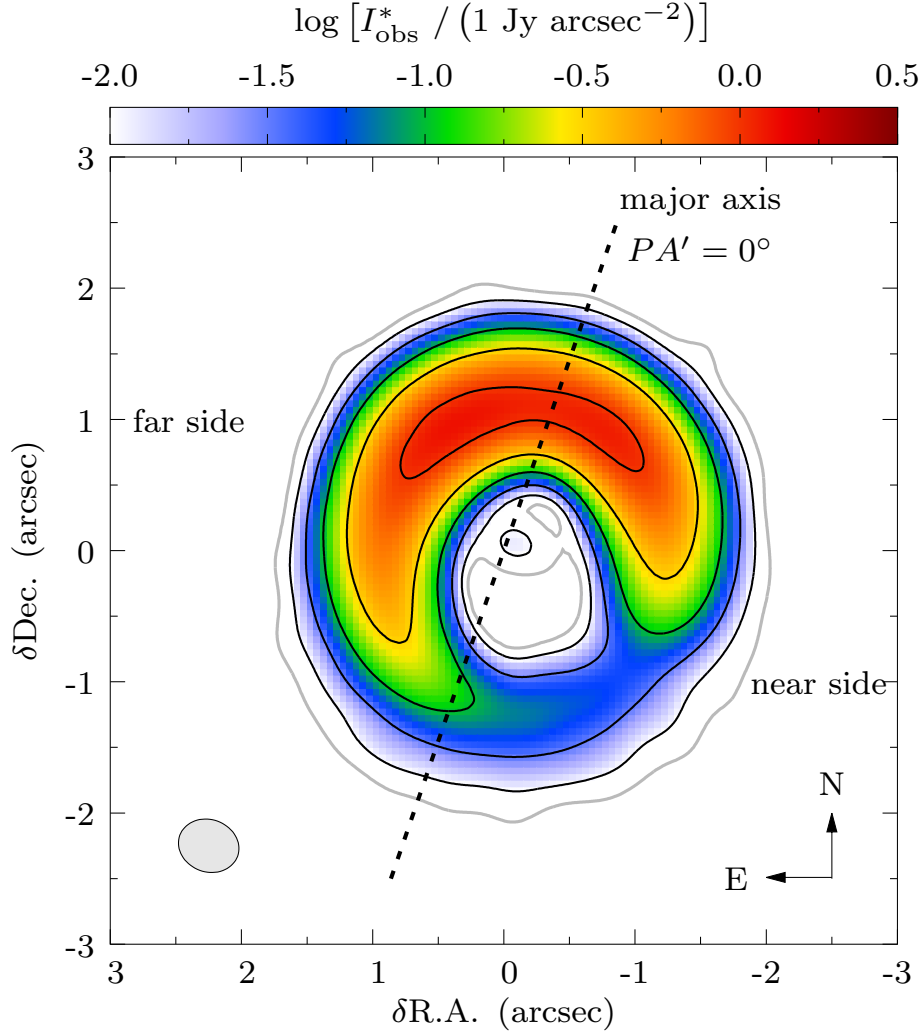


Figure 3.1: Image of the continuum emission at $\lambda_{\text{obs}} = 890 \mu\text{m}$ taken with ALMA in its Cycle 0; same as Figure 2.2 but the color scale is in units of Jy arcsec^{-1} . North is up and east is to the right. The black contours denote the observed intensity I_{obs}^* at $\log(I_{\text{obs}}^*) = -2.0, -1.5, -1.0, -0.5, 0.0$. The root-mean-square noise level of the image is $\sigma_{\text{noise}} = 0.61 \text{ mJy arcsec}^{-2}$, and intensity five times of which is denoted by the gray contours. The synthesized beam is shown in the bottom left corner; the beam is $0''.47 \times 0''.40$ in FWHM and its major axis is oriented in $PA = 59^\circ.9$. The far side is in the northeast while the near side is in the southwest. The major axis of the disk is along $PA' = 0^\circ$; PA' is related to PA by $PA' = PA - 19^\circ$.

in Table 3.1. From here onwards, I will use PA' , the angle measured from the disk major axis, to denote the azimuthal position of the disk instead of PA ; the two are related by $PA' = PA + 19^\circ$. Equation (3.1) is a function of PA' , which has been omitted for convenience.

3.2 Physical assumptions on disk properties

3.2.1 Structure of disk model

The goal of this modeling is to derive the dust surface density distribution for the disk around HD 142527 that reproduces $I_{0,\text{obs}}^*$, $w_{0,\text{obs}}^*$, and $r_{0,\text{obs}}^*$ in each PA' sector. As can be seen in Figure 3.1, since the observed intensity of the disk varies smoothly in the azimuthal

Table 3.1: Gaussian-fitted results for the observed radial intensity profiles.

PA'	$I_{0,\text{obs}}^*$ (Jy arcsec ⁻²)	$w_{0,\text{obs}}^*$ (au)	$r_{0,\text{obs}}^*$ (au)
10° – 30°	1.16	50.9	158.4
30° – 50°	1.25	51.0	152.3
50° – 70°	1.19	50.2	148.6
70° – 90°	0.94	49.0	143.1
90° – 110°	0.72	47.0	142.6
110° – 130°	0.55	45.9	145.2
130° – 150°	0.39	45.5	150.6
150° – 170°	0.22	45.6	159.7
170° – 190°	0.11	46.5	169.5
190° – 210°	0.07	47.8	179.2
210° – 230°	0.06	50.5	178.3
230° – 250°	0.05	51.6	174.1
250° – 270°	0.13	47.9	161.5
270° – 290°	0.34	48.7	158.9
290° – 310°	0.62	48.2	157.9
310° – 330°	0.96	48.5	158.6
330° – 350°	1.16	48.3	160.4
350° – 10°	1.13	49.3	159.9

direction, it is considered appropriate to employ a two-dimensional, axisymmetric disk model. In addition, the disk model is also configured to be mirror symmetric with respect to the midplane. This simplified disk model will be used as a fiducial model to reproduce the intensity profile in each sector individually. In this work, self-scattering of dust grains is considered. The scattered light of the observed crescent disk, however, may be different from that of the axisymmetric model when scattering is dominant; the validity of this approach is discussed in [Section 5.4](#).

The cylindrical coordinates (r, ϕ, z) are used to denote the intrinsic coordinates of the disk model; $z = 0$ plane corresponds to the disk midplane, while r the radial distance and ϕ the azimuthal angle. Since the observed radial profiles can be well fitted by a Gaussian function [cf. [Equation \(3.1\)](#)], the dust surface density distribution is assumed to be following a similar distribution thereof, described by

$$\Sigma(r, \phi; \Sigma_0, w_0, r_0) = \Sigma_0 \exp \left\{ \min \left[- \left(\frac{r - r_0}{w_0} \right)^2, -20 \right] \right\}, \quad (3.2)$$

where Σ_0 , w_0 , and r_0 denote the peak surface density, the radial width of the distribution, and the location radius of Σ_0 , respectively; they are the free parameters in the modeling. The model is axisymmetric so the dependence on ϕ vanishes. The star is located at the origin, and the surface density Σ at each radii is obtained by integrating the dust spatial density

$\rho(r, z)$ along the z direction. The floor surface density of magnitude $\exp(-20)$ is set for computational convenience. Equation (3.2) is the same as Equation (2.1), but we dropped the subscript “d” denoting “dust”. Neither the effects of disk accretion, nor the shadows cast by the inner warped disk as discussed by Marino, Perez, and Casassus (2015), is taken into account in this work.

3.2.2 Size distribution and opacity of dust grains

The dust grains in the disk are assumed to be compact spheres composed of silicate, carbonaceous compounds, and water ice; their mass fractional abundances relative to the hydrogen mass are taken to be 0.0043, 0.0030, and 0.0094, respectively, which are consistent with the solar elemental abundance (Anders and Grevesse, 1989). The grains have the power-law size distribution,

$$n(a) \propto a^{-p}, \quad a_{\min} \leq a \leq a_{\max}, \quad (1.4)$$

where $a_{\min} = 0.01 \mu\text{m}$, $a_{\max} = 1 \text{ mm}$, and $p = 3.5$. The choice of $a_{\max}$ is based on the observed flux slope shown in Figure 2.1; the slope at the radio wavelengths is $\alpha \approx 3$, which implies $\beta \approx 1$ (Verhoeff et al., 2011), indicating the grains in the disk are larger than those in the ISM. In the disk, the grain size is most likely to be spatial dependence, however to facilitate the parameter search a fixed size distribution is applied. In addition, when $a_{\max}$ is comparable to the observation wavelength, the dust opacity is large thus derived results of surface density can be considered as lower limit.

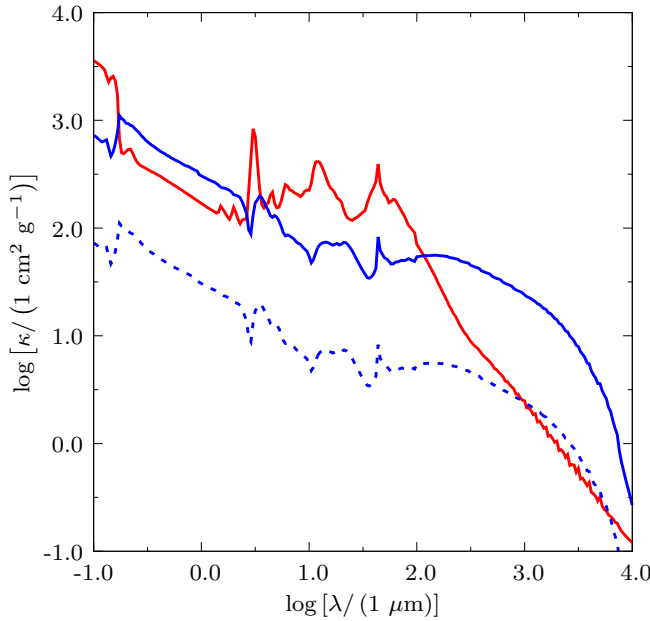


Figure 3.2: The conventional values of the absorption opacity κ_a (black solid line) and the scattering opacity κ_s (red dashed line) per unit dust mass, for compact dust grains following distribution $a^{-3.5}$, with $a_{\max} = 1 \text{ mm}$. The blue dashed line indicates the scattering opacity reduced to 10% from their conventional values.

The absorption and scattering cross sections² $C_a(a)$ and $C_s(a)$, and the asymmetry parameter $g(a)$ ³ for every grain size in the power-law distribution are calculated using the

²Frequency notation ν in $C_a(a; \nu)$ and $C_s(a; \nu)$ are omitted for convenience. See Footnote 5.

³The asymmetry parameter describes the anisotropy in scattering and takes value within $|g| \leq 1$ (see, e.g., Bohren and Huffman, 1983). For symmetric scattering about the axis perpendicular to the propagation

Mie theory. The scattering cross section and its asymmetry parameter are defined as

$$C_s(a) = \int_{4\pi} \frac{dC_s(a)}{d\Omega} d\Omega \quad (3.3)$$

and

$$g(a) = \frac{1}{C_s(a)} \int_{4\pi} \frac{dC_s(a)}{d\Omega} \cos \Theta(a) d\Omega, \quad (3.4)$$

respectively, where $dC_s(a)/d\Omega$ is the differential scattering cross section and $\Theta(a)$ the deflection angle from the propagation direction of an incident wave, $\Theta(a) = 0^\circ$. To take into account the effects of asymmetric scattering in the M1 model (see [Section 3.3.1](#)), the asymmetry parameter is incorporated by multiplying $C_s(a)$ by $[1 - g(a)]$; the light scattered away from the propagation direction is treated as extinction along $\Theta = 0^\circ$. In this way, the effects of self-scattering are considered while keeping the computational time for radiative transfer reasonable. Denoting the grain mass by $m(a)$, the scattering opacity used in this study is then defined as

$$\kappa_s = \int \left\{ \frac{C_s(a)}{m(a)} [1 - g(a)] \right\} \frac{dn(a)}{da} da, \quad (3.5)$$

which is weighted by the size distribution. Similarly, dividing $C_a(a)$ by $m(a)$ and integrate over the size distribution we obtain the absorption opacity as

$$\kappa_a = \int \left\{ \frac{C_a(a)}{m(a)} \right\} \frac{dn(a)}{da} da. \quad (3.6)$$

The opacities are shown in [Figure 3.2](#). When $a_{\max}$ is comparable to λ_{obs} , κ_s is larger than κ_a by a factor of about 10; $\kappa_a = 2.9 \text{ cm}^2 \text{ g}^{-1}$ and $\kappa_s = 26.2 \text{ cm}^2 \text{ g}^{-1}$ at $\lambda_{\text{obs}} = 890 \text{ } \mu\text{m}$ ([Aikawa and Nomura, 2006](#)). As in [Section 5.1](#), I also use model where κ_s is reduced by 90% from the conventional value.

3.3 Modeling procedure

[Figure 3.3](#) is a flow chart showing the modeling procedure. The sequence is repeated until a set of best-fit (Σ_0, w_0, r_0) is found for each of the 18 sectors. The procedures are summarized as follows.

- (1) Determine the free parameters that describe the surface density distribution, i.e., Σ_0 , w_0 , and r_0 . The model parameters in this study are listed in [Table 3.2](#).
- (2) Calculate the radiative transfer by the M1 method along with the hydrostatic equilibrium, to obtain the self-consistent dust grain spatial distribution ρ , the temperature field T , and the mean intensity J_ν , meanwhile satisfying the dust distribution in [Equation \(3.2\)](#). The disk structure and the dust opacity assumed in [Section 3.2](#) are taken into consideration during the calculations.
([Section 3.3.1](#))

direction of an incident wave, $g = 0$. If the grain tends to scatter light toward the forward direction, g is positive. Contrarily, backward scattering has a negative g value.

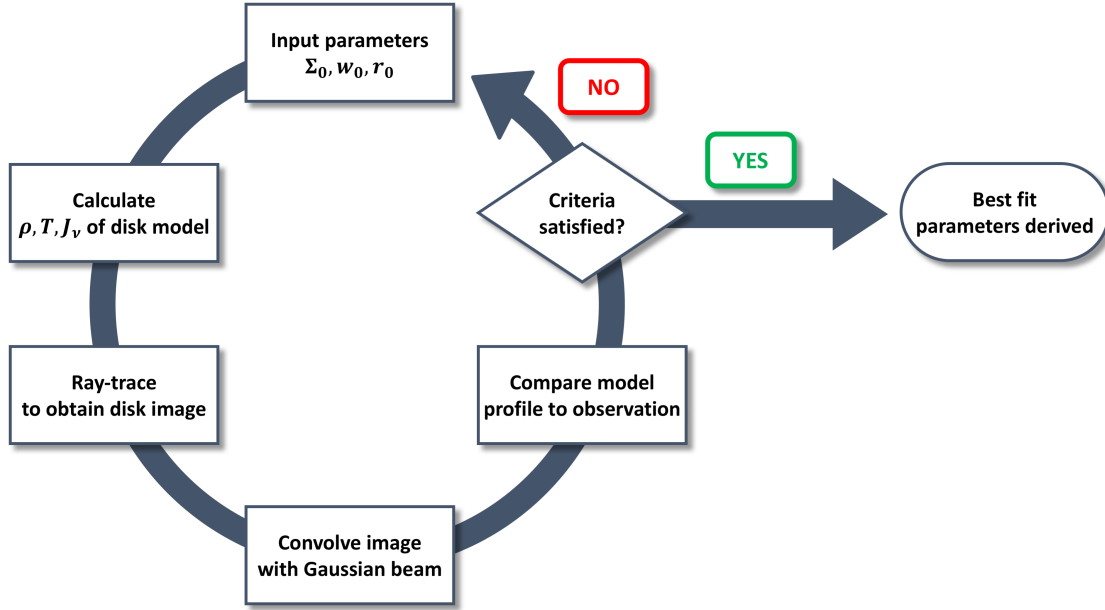


Figure 3.3: The modeling flow chart to derive best-fit parameters (Σ_0, w_0, r_0) for each of the 18 sectors.

- (3) By using the calculated ρ , T , J_ν of the disk model, intensity of the dust emission is ray-traced to obtain a disk model image.
(Section 3.3.2)
- (4) In order to mimic the observation, the image is convolve with a Gaussian beam similar to the synthetic beam of the actual observation by ALMA. Next extract radial intensity profiles from the convolved image and fit the model profiles with a Gaussian function to obtain I_0^* , w_0^* , and r_0^* ; these are similar procedure applied to the observed profiles which is described in Section 3.1.
(Section 3.3.3)
- (5) The model (I_0^*, w_0^*, r_0^*) are compared with $(I_{0,\text{obs}}^*, w_{0,\text{obs}}^*, r_{0,\text{obs}}^*)$ in the same PA' sector. The best-fit values have to satisfy the criteria Equation (3.26). If necessary, construct a refined model by interpolating between Σ_0 models or r_0 models.
(Section 3.3.4)

The details of each step is discussed next.

Table 3.2: The parameters setup for the dust surface density distribution.

Parameter	Range	In steps of
Σ_0 (g cm^{-2})	$-2.1 \leq \log \Sigma_0 \leq 0.1$	$\log \Sigma_0 = 0.1$
w_0 (au)	$^{\dagger}21 \leq w_0 \leq 31$	$w_0 = 2$ au
r_0 (au)	$159 \leq r_0 \leq 199$	$r_0 = 2$ au

[†] Models of $w_0 = 32$ au are also included in the setup.

3.3.1 Radiative transfer in the disk

The radiation transfer of the disk model I used is calculated by the M1 method⁴(González, Audit, and Huynh, 2007). The recipe is summarized as follows.

At coordinate $\mathbf{x}$ and at time t , the radiation transfer equation for the specific intensity $I_\nu(\mathbf{x}, t; \mathbf{n})$ along direction $\mathbf{n}$ is (see, e.g., Shu, 1991)

$$\begin{aligned} \frac{1}{c} \frac{\partial I_\nu(\mathbf{x}, t; \mathbf{n})}{\partial t} + \mathbf{n} \cdot \nabla I_\nu(\mathbf{x}, t; \mathbf{n}) = \\ \kappa_a \rho(\mathbf{x}, t) B_\nu(\mathbf{x}, t) - (\kappa_a + \kappa_s) \rho(\mathbf{x}, t) I_\nu(\mathbf{x}, t; \mathbf{n}) + \kappa_s \rho(\mathbf{x}, t) \int_{4\pi} I_\nu(\mathbf{x}, t; \mathbf{n}') d\mathbf{n}', \end{aligned} \quad (3.7)$$

where κ_a and κ_s are the opacities defined by Equations (3.5) and (3.6), while c and ρ the speed of light and the matter density. On the right hand side of the equation, the first term states that emissivity of the matter, in which case is the dust grains, is proportional to the blackbody radiation B_ν at temperature T , while the second term is read as extinction by the matter. The last term, on the other hand, represents the intensity scattered by the dust grains from $\mathbf{n}'$ into $\mathbf{n}$. Integrating Equation (3.7) over all solid angle, and integrating similarly the dot product of Equation (3.7) between $\mathbf{n}$, we obtain

$$\frac{\partial E_\nu}{\partial t} + \nabla \cdot \mathbf{F}_\nu = \kappa_a \rho (4\pi B_\nu - c E_\nu), \quad (3.8)$$

$$\frac{\partial \mathbf{F}_\nu}{\partial t} + c^2 \nabla \cdot \mathcal{P}_\nu = -(\kappa_a + \kappa_s) c \rho \mathbf{F}_\nu, \quad (3.9)$$

respectively. Here, E_ν , $\mathbf{F}_\nu$, and $\mathcal{P}_\nu$ are defined as

$$\begin{aligned} E_\nu &= \int_{4\pi} I_\nu(\mathbf{x}, t; \mathbf{n}) d\mathbf{n}, \\ \mathbf{F}_\nu &= \int_{4\pi} \mathbf{n} I_\nu(\mathbf{x}, t; \mathbf{n}) d\mathbf{n}, \\ \mathcal{P}_\nu &= \int_{4\pi} \mathbf{n} \mathbf{n} I_\nu(\mathbf{x}, t; \mathbf{n}) d\mathbf{n}, \end{aligned}$$

i.e., they are the zeroth, the first, and the second angular moments of the intensity, respectively. Equations (3.8) and (3.9) are the conservation equations of energy and momentum, written by assuming coherent scattering whereby the last term on the right hand side of Equation (3.7) vanishes. The conservation equations are closed by relating $\mathcal{P}_\nu$ and E_ν via

$$\mathcal{P}_\nu = \left(\frac{1 - \chi_\nu}{2} \mathcal{I} + \frac{3\chi_\nu - 1}{2} \frac{\mathbf{f}_\nu \mathbf{f}_\nu}{|\mathbf{f}_\nu|^2} \right) E_\nu, \quad (3.10)$$

where

$$\begin{aligned} \chi_\nu &= \frac{3 + 4|\mathbf{f}_\nu|^2}{5 + \sqrt{4 - 3|\mathbf{f}_\nu|^2}}, \\ \mathbf{f}_\nu &\equiv \frac{\mathbf{F}_\nu}{c E_\nu}, \end{aligned}$$

⁴Different from the flux diffusion approximation which considers only the zeroth moment of intensity, the M1 method takes account of the zeroth and the first moments of intensity in the radiative transfer. The former method is relatively accurate in the limit of optically thick region, but may not appropriately describe optically thin and shadowed regions.

and $\mathcal{I}$ the identity matrix.

In the cylindrical coordinates of the disk model (see [Section 3.2](#)), the star locates at the origin and the disk is symmetric around the z -axis as well as with respect to the midplane. We consider the star as the heat source for the disk, and use 226 colors within $0.1 \mu\text{m} \leq \lambda \leq 3.16 \text{ mm}$ (equivalent spectral resolution of $\Delta \log \lambda = 0.02$) in the calculation. Decomposing the radiation energy density and the flux into the components each from the star and from the disk ([Kanno, Harada, and Hanawa, 2013](#)), we write

$$E_\nu(r, z) = E_{\nu, \text{star}}(r, z) + E_{\nu, \text{disk}}(r, z), \quad (3.11)$$

$$\mathbf{F}_\nu(r, z) = \mathbf{F}_{\nu, \text{star}}(r, z) + \mathbf{F}_{\nu, \text{disk}}(r, z). \quad (3.12)$$

The star is assumed to be a blackbody of effective temperature T_{eff} , and its radiation energy density and flux intercepted by the disk at (r, z) are evaluated as

$$E_{\nu, \text{star}}(r, z) = \frac{\pi R_{\text{star}}^2}{c(r^2 + z^2)} B_\nu(T_{\text{eff}}) \exp[-\tau(r, z)], \quad (3.13)$$

$$\mathbf{F}_{\nu, \text{star}}(r, z) = \frac{c}{\sqrt{r^2 + z^2}} \begin{pmatrix} r \\ z \end{pmatrix} E_{\nu, \text{star}}(r, z), \quad (3.14)$$

where the τ here (and here only) is defined as

$$\tau(r, z) = \int_0^r (\kappa_a + \kappa_s) \rho \left(r', \frac{zr'}{r} \right) \sqrt{1 + \left(\frac{z}{r} \right)^2} dr'. \quad (3.15)$$

The conservation equations in the disk then read

$$\frac{\partial E_{\nu, \text{disk}}}{\partial t} + \nabla \cdot \mathbf{F}_{\nu, \text{disk}} = \kappa_a \rho [4\pi B_\nu(T) - cE_{\nu, \text{disk}}] + \kappa_s \rho c E_{\nu, \text{star}}, \quad (3.16)$$

$$\frac{\partial \mathbf{F}_{\nu, \text{disk}}}{\partial t} + c^2 \nabla \cdot \mathcal{P}_{\nu, \text{disk}} = -(\kappa_a + \kappa_s) \rho c \mathbf{F}_{\nu, \text{disk}}. \quad (3.17)$$

Assuming the disk to be a static structure, the time evolution term for both $E_{\nu, \text{disk}}$ and $\mathbf{F}_{\nu, \text{disk}}$ equal zero.

Although in this work gas distribution is not a subject of modeling, the gas hydrostatic equilibrium in the disk vertical direction is calculated so that the dust grains can be allocated correspondingly with the same scale height as the gas. The gas and dust are assumed to be well mixed and they exist in a gas-to-dust ratio of 100 throughout the disk. In the vertical direction the gas pressure gradient and the z -component of the star gravity are in equilibrium

$$\frac{dP}{dz} = \frac{GM_{\text{star}}z}{(r^2 + z^2)^{3/2}} \rho_{\text{gas}}, \quad (3.18)$$

where G and M_{star} denote the gravitational constant and the mass of the star, respectively. The density of the gas is denoted by ρ_{gas} , and a hundredth of it is the dust spatial density ρ . The gas pressure P follows the ideal gas law, i.e.,

$$P = \frac{k_B}{\mu m_H} \rho_{\text{gas}} T, \quad (3.19)$$

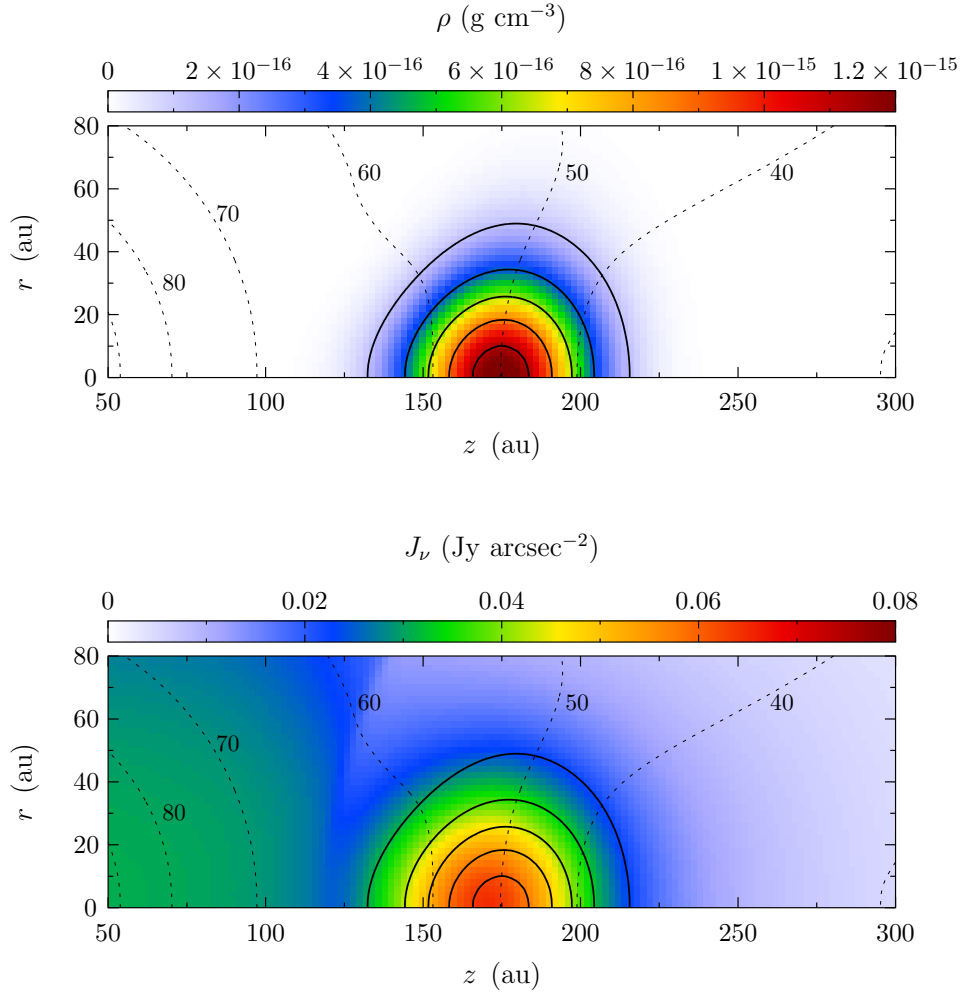


Figure 3.4: The horizontal axis denotes the radius from the central star located at $(r, z) = (0 \text{ au}, 0 \text{ au})$, while the vertical axis denotes the height from the disk midplane. The dust spatial density ρ (top panel) and the mean intensity J_ν (bottom panel) of the disk model with $\Sigma_0 = 0.01 \text{ g cm}^{-2}$, $w_0 = 27 \text{ au}$ and $r_0 = 175 \text{ au}$ are plotted as color. The spatial density is also plotted as solid line contours, where the densities are drawn at $\rho(r, z) = 0.1, 0.3, 0.5, 0.7, 0.9$ of $\rho_0(175 \text{ au}, 0 \text{ au})$, which is the peak density in the model. The temperature field T , in units of K, is plotted in each panel as dotted line contours.

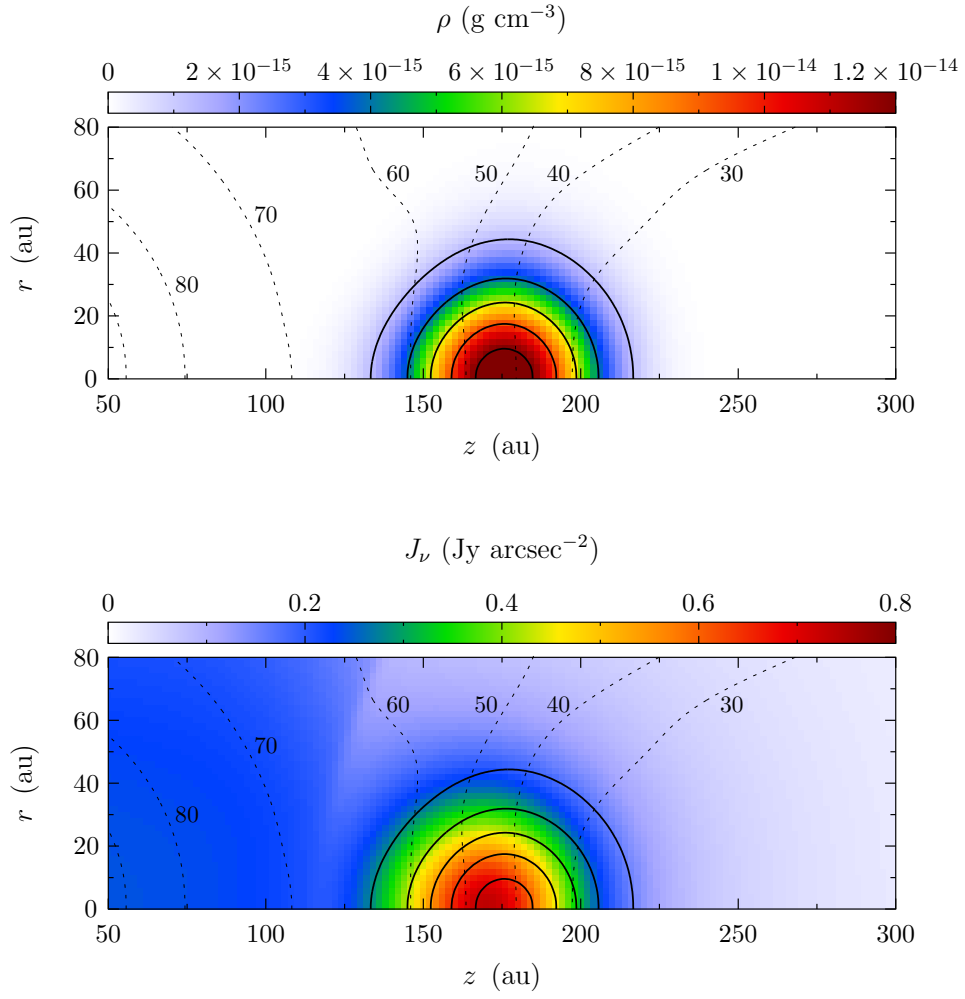


Figure 3.5: Similar to Figure 3.4 with the same w_0 and r_0 values, but a different dust surface density where $\Sigma_0 = 0.10$ g cm⁻². Notice the different color scale from the previous figure.

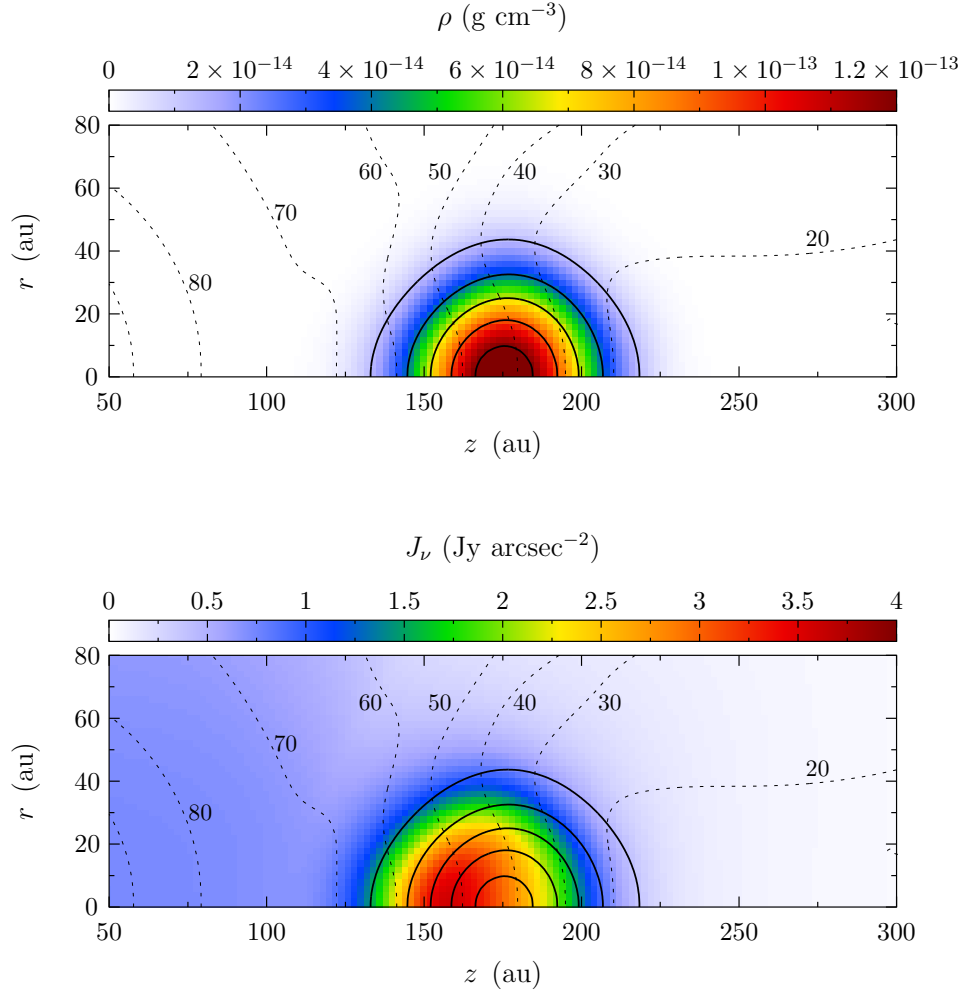


Figure 3.6: Similar to Figures 3.4 and 3.5 with the same w_0 and r_0 values, but a different dust surface density where $\Sigma_0 = 1.00 \text{ g cm}^{-2}$. Notice the different color scale from the previous figures.

where k_B denotes the Boltzmann constant and m_H the mass of hydrogen atom. The mean molecular weight is assumed to be $\mu = 2.339$. The dust temperature T at each location (r, z) satisfies the condition for thermal equilibrium,

$$\int \kappa_a [E_\nu - 4\pi B_\nu(T)] d\nu = 0. \quad (3.20)$$

The mean intensity J_ν is derived from

$$J_\nu = \frac{cE_\nu}{4\pi}. \quad (3.21)$$

The computation region covers $30 \text{ au} \leq r \leq 410 \text{ au}$ and $0 \text{ au} \leq z \leq 120 \text{ au}$ with a spatial resolution of 2 au.

The self-consistent distributions of ρ , T , and J_ν are shown in [Figures 3.4 to 3.6](#). The radial width of the disk model and the location radius of the peak Σ_0 are set constant, where $w_0 = 27 \text{ au}$ and $r_0 = 175 \text{ au}$, respectively, whereas the surface density is set at three different values at $\Sigma_0 = 0.01 \text{ g cm}^{-2}$, 0.10 g cm^{-2} , and 1.00 g cm^{-2} . As mentioned, the disk model is axisymmetric, so that ρ , T , and J_ν are independent of the azimuthal direction ϕ . Since the disk is in hydrostatic equilibrium in the z -direction and the dust surface density distribution follows the Gaussian function in [Equation \(3.2\)](#), the disk cross section in the (r, z) plane takes a nearly circular shape. It then can be visualized that the disk model forms a torus surrounding the central star.

3.3.2 Image of the disk model

With the two-dimensional dust spatial density ρ , temperature T , and mean intensity J_ν , an image of the disk model can be created by ray-tracing emergent intensity along the line of sight z' based on the transfer equation:

$$\frac{dI}{dz'} = -(\kappa_a + \kappa_s)\rho(I - S_\nu), \quad (3.22)$$

where the source function is given by

$$S_\nu = (1 - \eta) B_\nu(T) + \eta J_\nu. \quad (3.23)$$

The source function is the sum of the Planck function $B_\nu(T)$ and the angular-averaged intensity J_ν , each weighted by $(1 - \eta)$ and η , where

$$\eta \equiv \frac{\kappa_s}{\kappa_a + \kappa_s}, \quad (3.24)$$

is the albedo⁵. During the process the disk inclination $i = 27^\circ$ and the orientation of the major axis at $PA = 161^\circ$ are taken into account. The intensity distribution is calculated on an uniform grid of 2 au on the sky plane.

⁵Equivalently, by defining the photon destruction probability as

$$\epsilon = \frac{\kappa_a}{\kappa_a + \kappa_s},$$

the source function can be written as

$$S_\nu = \epsilon B_\nu(T) + (1 - \epsilon)J_\nu.$$

Figure 3.7 shows the intensity images obtained by ray-tracing for two Σ_0 models, 0.01 g cm^{-2} and 1.00 g cm^{-2} . The models are common in w_0 and r_0 , which are 27 au and 175 au, respectively. The coordinates of the disk projected in the sky are denoted by (r', PA') . The regions of $0^\circ < PA' < 180^\circ$ and $180^\circ < PA' < 360^\circ$ correspond to the far side and the near side of the disk, respectively, as seen from the observer. Although the disk model is an axisymmetric torus, the intensity varies azimuthally due to the disk inclination. In the lower Σ_0 model, the intensity peaks around the major axis. On the other hand, the higher Σ_0 model shows that the far side is the brightest, and it is significantly brighter than the near side.

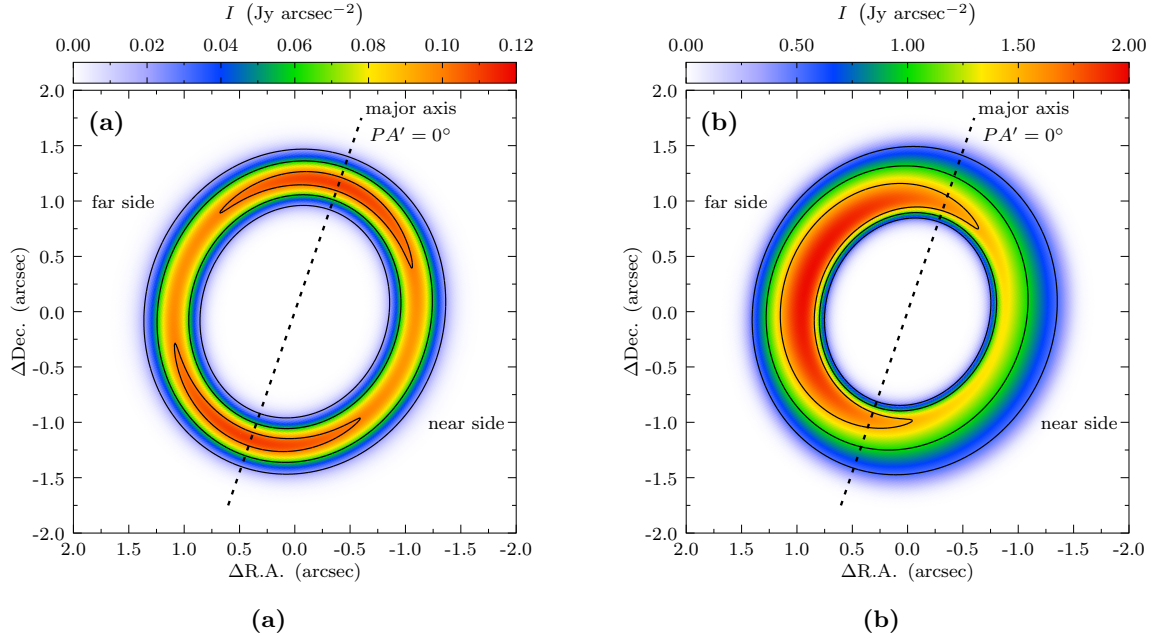


Figure 3.7: Disk intensity images obtained by ray-tracing simulation. The color scale denotes the intensity I before beam convolution. The dashed line indicates the major axis of the disk along $PA' = 0^\circ$. The models have $w_0 = 27 \text{ au}$ and $r_0 = 175 \text{ au}$. (a): $\Sigma_0 = 0.01 \text{ g cm}^{-2}$ model. The contours are drawn at $I = 0.02 \text{ Jy arcsec}^{-2}$, $0.06 \text{ Jy arcsec}^{-2}$, and $0.10 \text{ Jy arcsec}^{-2}$. (b): $\Sigma_0 = 1.00 \text{ g cm}^{-2}$ model. The contours are drawn at $I = 0.50 \text{ Jy arcsec}^{-2}$, $1.00 \text{ Jy arcsec}^{-2}$, and $1.50 \text{ Jy arcsec}^{-2}$.

We can define the effective optical thickness of the disk as

$$\tau_{\text{eff}} \approx \Sigma_0 \sqrt{\kappa_a (\kappa_a + \kappa_s)}. \quad (3.25)$$

A medium is optically thin or translucent if $\tau_{\text{eff}} \ll 1$, and it is optically thick or opaque if $\tau_{\text{eff}} \gtrsim 1$. Thus, the $\Sigma_0 = 0.01 \text{ g cm}^{-2}$ model with $\tau_{\text{eff}} \approx 0.1$ represents an optically thin disk, while the $\Sigma_0 = 1.00 \text{ g cm}^{-2}$ model is an optically thick disk as $\tau_{\text{eff}} \approx 1$. When $\tau_{\text{eff}} \ll 1$, the intensity is roughly proportional to the amount of dust along the line of sight. The major axis is highest in the intensity because the observer's line of sight intercepts the disk plane longer. On the contrary, if $\tau_{\text{eff}} \gtrsim 1$, only the dust grains at the disk surface can be observed, in which case it is not the dust surface density, but its temperature that becomes the determinant of the intensity. The temperature of the toric disk decreases with radius since it is heated by the central star, which can be confirmed from ???. When optically thick, the stellar radiation is greatly reduced at a particular surface of the torus facing the star. This surface is often

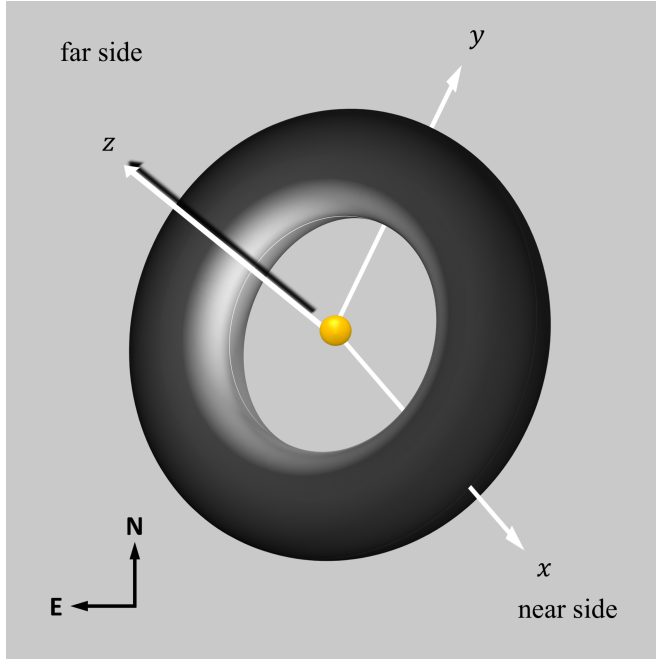


Figure 3.8: An illustration depicting an optically thick, inclined toric disk that resembles the case of high Σ_0 models where $\tau_{\text{eff}} > 1$. The temperature is indicated by the monochrome tones; the darker is the tone, the lower the temperature. The x -axis and the y -axis lie in the disk midplane, while the z -axis is perpendicular to it. The inner wall is the white-lit region facing the central star (the yellow sphere in the center).

called the hot inner wall, so termed since its temperature is the highest in the torus. The inner wall is illustrated in Figure 3.8. Keeping this in mind, we realize that the hot inner wall is exposed to us on the far side but hidden from us on the near side due to the disk inclination. As a result, the former region is brighter than the latter because of the difference in the temperature at the disk surface.

3.3.3 Beam convolution

The next step in imaging the disk model is the convolution of the ray-traced images with a Gaussian beam to mimic the observation, examples of which are shown in Figure 3.9. The intensity of the disk decreases after being spatially averaged by the beam. Since the beam is elliptical with its major axis lying along $PA' = 78.9^\circ$, the image no longer retains its reflection symmetry with respect to the disk minor axis ($PA' = 90^\circ$) after the convolution. From the convolved image the radial intensity profiles are extracted and are fitted with a Gaussian function to obtain I_0^* , w_0^* , and r_0^* , following the exact procedure described in Section 2.4.1. The asterisk (*) indicates quantity that are obtained from the beam-convolved images.

3.3.4 Modeling criteria

A repository of (I_0^*, w_0^*, r_0^*) is first created by performing step (1) to step (4) in the modeling sequence for models of (Σ_0, w_0, r_0) which can be configured from the parameter space listed in Table 3.2; (I_0^*, w_0^*, r_0^*) and (Σ_0, w_0, r_0) are thus in a one-to-one relation. The parameter search is carried out by comparing the observed $(I_{0,\text{obs}}^*, w_{0,\text{obs}}^*, r_{0,\text{obs}}^*)$ to the repository of (I_0^*, w_0^*, r_0^*) obtained from the models, based on the following criteria:

$$|\Delta I_0^*| \equiv |I_{0,\text{obs}}^* - I_0^*| \leq 0.01 I_{0,\text{obs}}^*, \quad (3.26a)$$

$$|\Delta w_0^*| \equiv |w_{0,\text{obs}}^* - w_0^*| \leq 1 \text{ au}, \quad (3.26b)$$

$$|\Delta r_0^*| \equiv |r_{0,\text{obs}}^* - r_0^*| \leq 1 \text{ au}. \quad (3.26c)$$

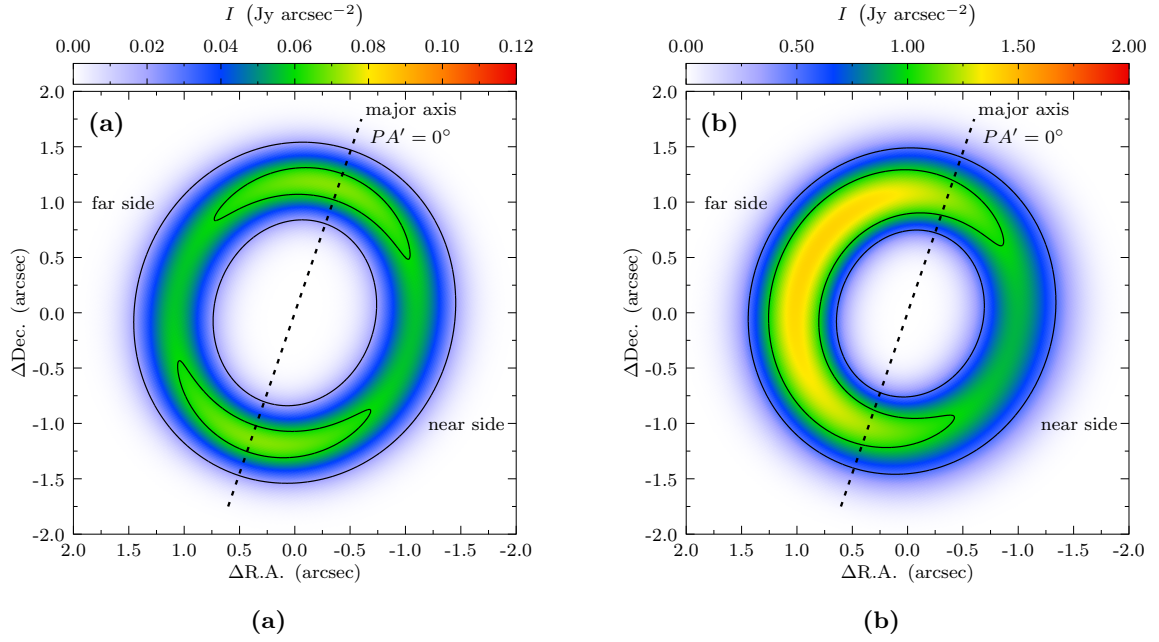


Figure 3.9: Similar to Figure 3.7, but the images here are obtained by convolving the ray-traced images in Figure 3.7 with a Gaussian beam of the exact FWHM and orientation as the actual observation by ALMA. The color scales in both Σ_0 models are the same as their counterpart in Figure 3.7. (a): $\Sigma_0 = 0.01 \text{ g cm}^{-2}$ model. The contours are drawn at $I = 0.02 \text{ Jy arcsec}^{-2}$ and $0.06 \text{ Jy arcsec}^{-2}$. (b): $\Sigma_0 = 1.00 \text{ g cm}^{-2}$ model. The contours are drawn at $I = 0.50 \text{ Jy arcsec}^{-2}$ and $1.00 \text{ Jy arcsec}^{-2}$.

The set of (Σ_0, w_0, r_0) associated with (I_0^*, w_0^*, r_0^*) that satisfies the above criteria is the best-fit set for the sector. In this work, I adapt conditions stricter than the $\pm 10\%$ tolerance applied by Muto et al. (2015) to all the criteria above, so that the slight difference in the smooth $(I_{0,\text{obs}}^*, w_{0,\text{obs}}^*, r_{0,\text{obs}}^*)$ transition between the sectors can be distinguished. Parameters that successfully meet all the criteria in Equation (3.26) are considered as the best-fit values in reproducing the observed radial intensity profiles.

Aiming at saving computational time and therefore facilitating parameter search, I interpolate among the models to complement the sample on Σ_0 and r_0 . The interpolation involves four adjacent (Σ_0, w_0, r_0) models at the disk location (r, z) , and is done by the following weighted average:

$$A(r, z; \Sigma_{0,i}, w_0, r_{0,i}) = \sum_{n=1}^2 l_n \left[\sum_{m=1}^2 k_m A(r + r_{0,m} - r_{0,i}, z; \Sigma_{0,n}, w_0, r_{0,m}) \right], \quad (3.27)$$

where A represents ρ , T , or J_ν . The weighting factors k_m and l_n are defined as

$$\begin{aligned} k_1 &= 1 - \left| \frac{r_{0,i} - r_{0,1}}{r_{0,2} - r_{0,1}} \right| \\ k_2 &= 1 - k_1 \\ l_1 &= 1 - \left| \frac{\Sigma_{0,i} - \Sigma_{0,1}}{\Sigma_{0,2} - \Sigma_{0,1}} \right| \\ l_2 &= 1 - l_1 \end{aligned}$$

The subscripts “1” and “2” specify the two existing models, while the subscript “i” specifies the interpolated product. Interpolation on w_0 is not carried out because its 2-au interval in the parameter space is sufficiently refined to fulfill Equation (3.26b).

3.4 Definition of optical thickness

Table 3.3: The three definitions of optical thickness in this thesis.

Notation	Referred as	Defintion
τ_{eff}	effective optical thickness	$\tau_{\text{eff}} \approx \Sigma_0 \sqrt{\kappa_a(\kappa_a + \kappa_s)}$
τ	optical thickness	$\tau(z') = \int_{z'} \rho(\kappa_a + \kappa_s) dz'$
τ_{los}	optical thickness in the line of sight	$\tau_{\text{los}}(z') = - \int_{z'} \rho(\kappa_a + \kappa_s) dz'$

Before proceeding, I discuss the definition for three optical thicknesses that will be used henceforth. They are summarized in Table 3.3. They will also be related to the transfer equation, Equation (3.22).

The first definition for the optical thickness is the effective optical thickness τ_{eff} that appeared in Section 3.3.2:

$$\tau_{\text{eff}} \approx \Sigma_0 \sqrt{\kappa_a(\kappa_a + \kappa_s)}. \quad (3.25 \text{ revisited})$$

As mentioned, the transparency of a medium is characterized by its τ_{eff} ; translucent if the value is smaller than unity, and opaque otherwise. The second optical thickness is defined as

$$\tau(z') = \int_{z'} \rho(\kappa_a + \kappa_s) dz'. \quad (3.28)$$

This definition of τ is different from τ_{eff} ; the former follows a photon in its traveling path and describes the probability of extinction in every absorption and scattering event encountered by the photon, while the latter characterizes the transparency of the medium as a whole by taking account of the diffusion length of the photon in the presence of scattering (Rybicki and Lightman, 1979). These two optical thickness can be related to each other by

$$\tau_{\text{eff}} = \tau \sqrt{\frac{\kappa_a}{\kappa_a + \kappa_s}} = \tau \epsilon^{1/2} = \tau(1 - \eta)^{1/2}. \quad (3.29)$$

The second definition lets us rewrite the transfer equation as

$$\frac{dI}{d\tau} = -(I - S_\nu), \quad (3.30)$$

after dividing both sides of Equation (3.22) by $\rho(\kappa_a + \kappa_s)$ and assuming that the opacities are constant throughout the medium. Integrating Equation (3.30) with respect to τ , we obtain the formal solution of the transfer equation,

$$I(\tau) = I(0)e^{-\tau} + \int_{\tau} e^{-(\tau-\tau')} S_\nu(\tau') d\tau', \quad (3.31)$$

where $I(0)$ is the background intensity at $\tau = 0$. A simplified condition is when the medium is homogenous, so that the transfer equation reads

$$I(\tau) = S_\nu(\tau) + e^{-\tau}[I(0) - S_\nu(\tau)]. \quad (3.32)$$

From the above equation, we realize that if $\tau \ll 1$ then the emergent intensity is proportional to τ . On the other hand, if $\tau \gg 1$ the intensity conforms to S_ν .

The third definition of optical thickness is one that is integrated along the observer's line of sight, following

$$\tau_{\text{los}}(z') = - \int_{z'} \rho(\kappa_a + \kappa_s) dz', \quad (3.33)$$

i.e., it is integrated in the exact opposite direction as τ . I will be referring τ simply as the optical thickness, and τ_{los} as the optical thickness in the line of sight. In terms of τ_{los} , the formal solution of the transfer equation can be written as

$$I(\tau_{\text{los}}) = \int_{\tau'_{\text{los}}} e^{-\tau'_{\text{los}}} S_\nu(\tau'_{\text{los}}) d\tau'_{\text{los}}, \quad (3.34)$$

where a constant opacity is assumed in the medium. The observer can essentially observe the medium up to a location where $\tau_{\text{los}} = 1$, which we conveniently call it as the photosphere because when τ_{los} is greater than unity $S_\nu(\tau_{\text{los}})$ will be attenuated by more than 63% before reaching the observer. Therefore, the source function of the photosphere will contribute most of the intensity observed.

Chapter summary

1. This chapter summarizes the disk model and the procedure of searching best-fit parameters which can reproduce the observed dust continuum emission of the disk around HD 142527. The radial intensity profiles obtained from the dust continuum emission image reduced by [Muto et al. \(2015\)](#) at $\lambda_{\text{obs}} = 890 \mu\text{m}$ are the subject of modeling.
2. This work focuses on deriving the dust surface distribution for the whole disk, whereas [Muto et al. \(2015\)](#) modeled both gas and dust surface density, albeit for two sectors of the disk only.
3. The assumptions on disk structure and the dust properties, as well as the modeling procedure follow that of [Muto et al. \(2015\)](#). The modeling criteria, however, is set to be stricter in this work in order to distinguish the difference in the azimuthal sectors.
4. In order to facilitate further discussions in succeeding chapters, three definitions of optical thickness, τ_{eff} , τ , and τ_{los} , are introduced in the end of the chapter.

Chapter 4

Results of modeling

In this chapter, I present the modeling results of the dust surface density distribution for the disk around HD 142527. I will also discuss the problem when modeling the northwest sectors of the disk as a result of heavy scattering. The uncertainties of the derived values will also be estimated.

4.1 Derived best-fit values

Based on the modeling procedure discussed in [Chapter 3](#), I searched for the best-fit (Σ_0, w_0, r_0) that reproduces the radial intensity profiles of the disk around HD 142527. The results are shown in [Figure 4.1](#) and the detailed parameters are listed in [Table 4.1](#). The mass contained in each PA' sector is denoted by M_{sec} . Of the 18 radial intensity profiles, 15 of them are well reproduced by the models. However, none of the models succeed in reproducing the three radial profiles in $PA' = 310^\circ - 10^\circ$; the details of these sectors in the northwest region of the disk will be discussed separately in [Section 4.2](#).

In [Figure 4.2](#) the derived best-fit (Σ_0, w_0, r_0) and M_{sec} are plotted as a function of PA' . The dust peak surface density Σ_0 is highest in $PA' = 30^\circ - 50^\circ$, corresponding exactly to the brightest region in the ALMA submillimeter observation. From there Σ_0 decreases gradually toward the south and reaches a minimum in $PA' = 230^\circ - 250^\circ$, which is the faintest region in the observation. The Σ_0 values are 1.12 g cm^{-2} and $8.31 \times 10^{-3} \text{ g cm}^{-2}$, respectively, for the two sectors; they are different by a factor of ~ 130 , in contrast to the factor of ~ 70 obtained by [Muto et al. \(2015\)](#). Deferring the details to [Section 4.3](#), it is the different tolerance range in the modeling criteria that underlies the discrepancy between our results. From the minimum in $PA' = 230^\circ - 250^\circ$ Σ_0 rises toward the north. Excluding the three sectors in the northwest region, we obtained a Σ_0 distribution that is consistent with the observed lopsided disk seen in the dust continuum emission. In addition, M_{sec} distributes similar to Σ_0 along the azimuthal direction. On the other hand, w_0 correlates with r_0 , such that the wider is the disk, the further is it from the central star.

The disk model might overestimate the temperature in the north ($PA' \approx 11^\circ$) and the south ($PA' \approx 191^\circ$) of the outer disk, as the possible shadowing effects caused by the warped inner disk ([Marino, Perez, and Casassus, 2015](#); [Casassus et al., 2015](#)) is not accounted for. As a consequence, the best-fit Σ_0 for $PA' = 150^\circ - 170^\circ$, as well as the searched parameters for $PA' = 350^\circ - 10^\circ$, might be considered as lower limits.

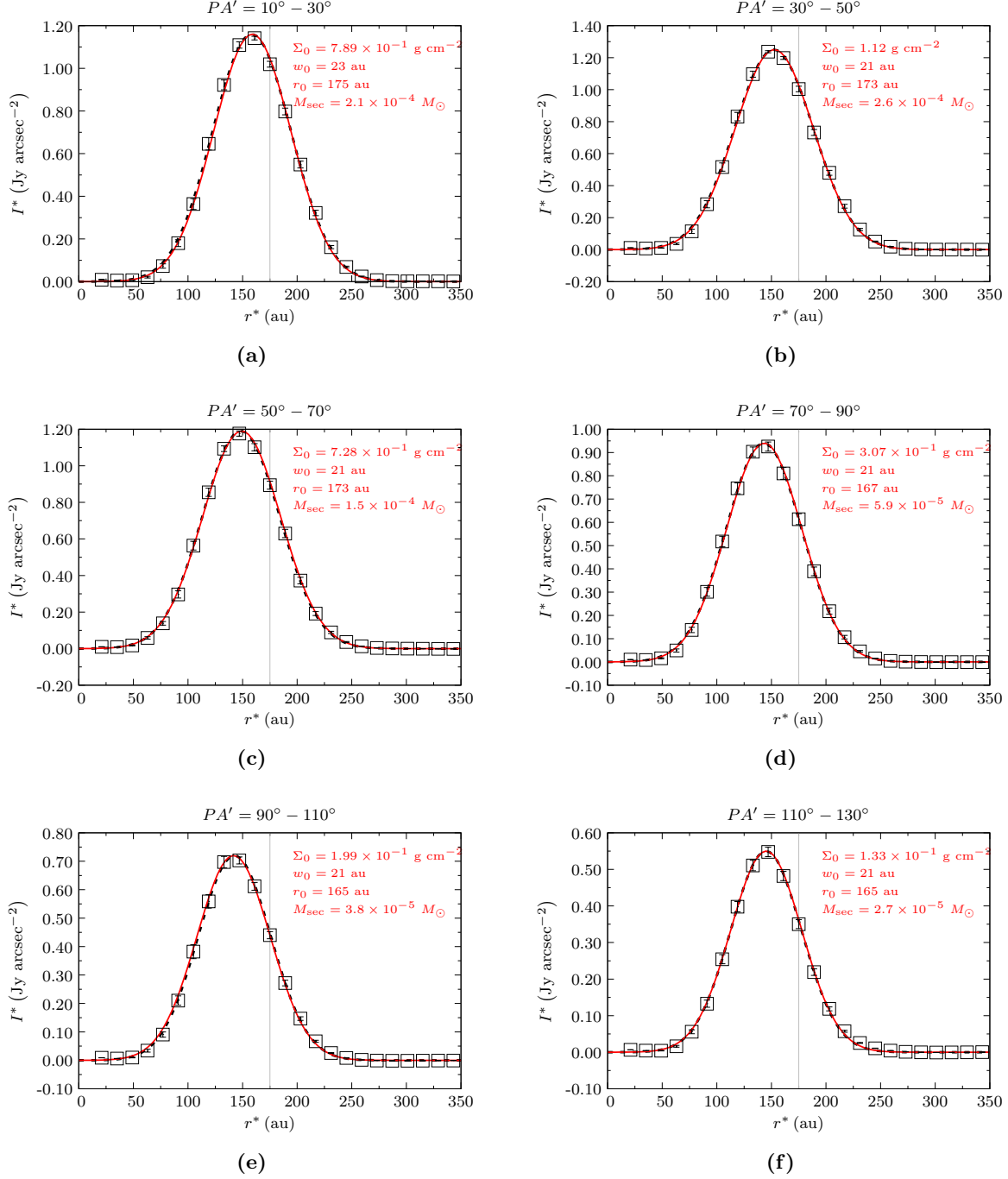


Figure 4.1: The observed radial intensity profiles (plotted in square boxes with error bars in the I_{obs}^* direction) at $\lambda_{\text{obs}} = 890 \mu\text{m}$ of the PA' sectors. Black dashed lines are Gaussian-fitted curves for the observational data points. The faint gray line at $r^* = 175$ au is drawn to emphasize the relative position of $I_{0,\text{obs}}^*$ among the PA' sectors. Red solid lines are the modeling results using the conventional model for dust opacity. The best-fit parameters and the disk mass of the sector are written on the top right in each plot.

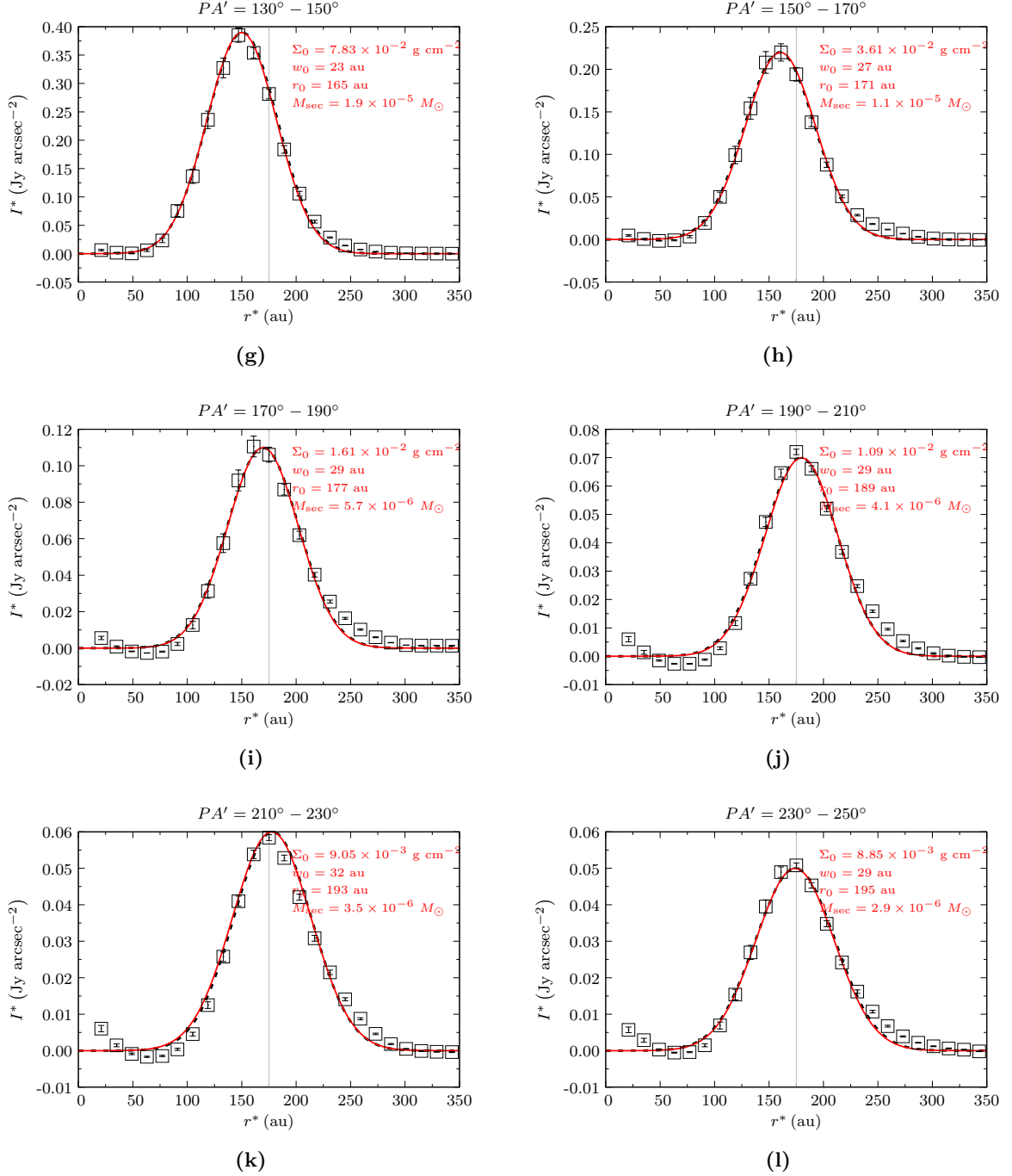


Figure 4.1: Continued.

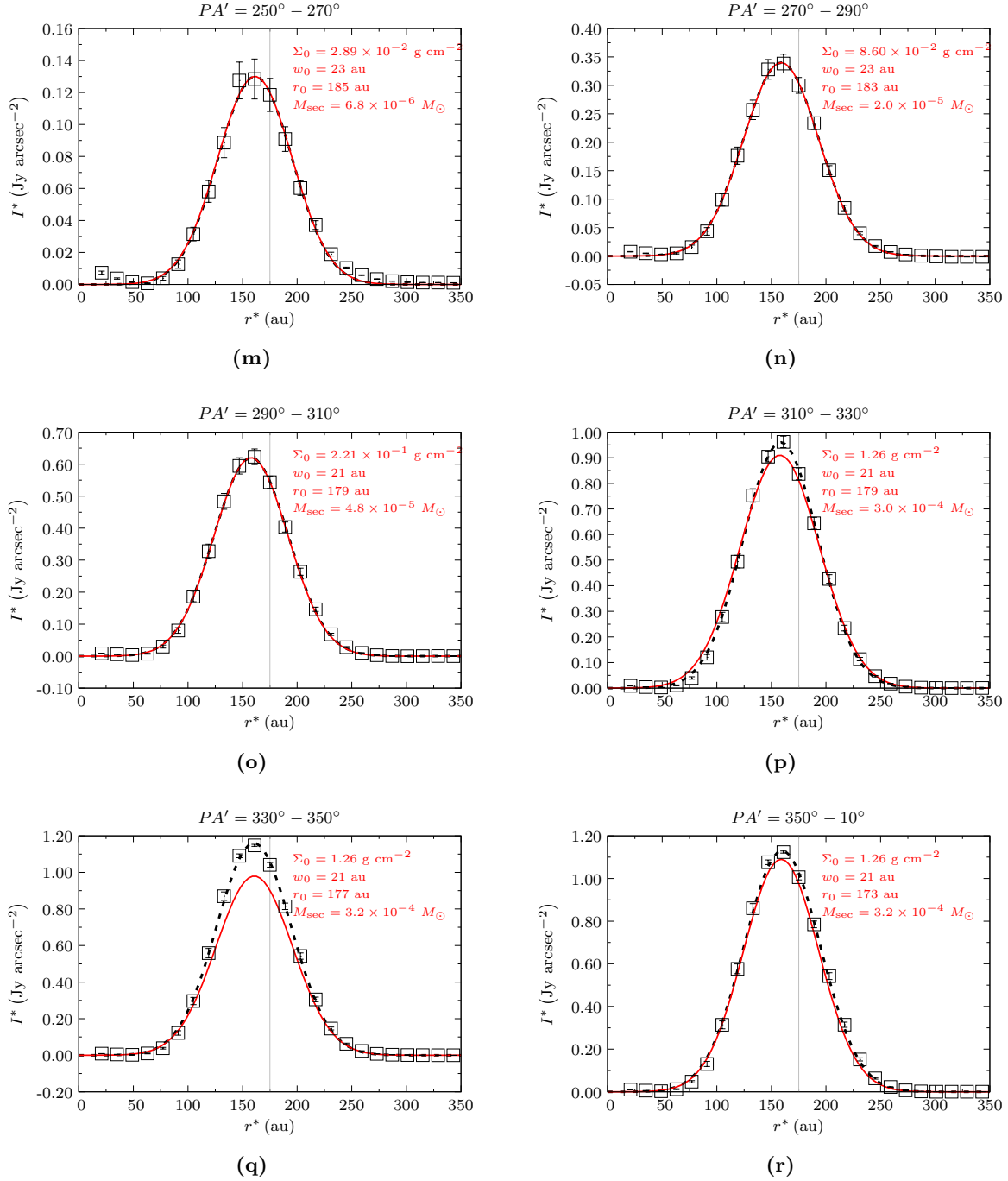


Figure 4.1: Continued. Note that the modeling results for $PA' = 310^\circ - 330^\circ$, $PA' = 330^\circ - 350^\circ$, and $PA' = 350^\circ - 10^\circ$ do not fulfill the criteria in Equation (3.26).

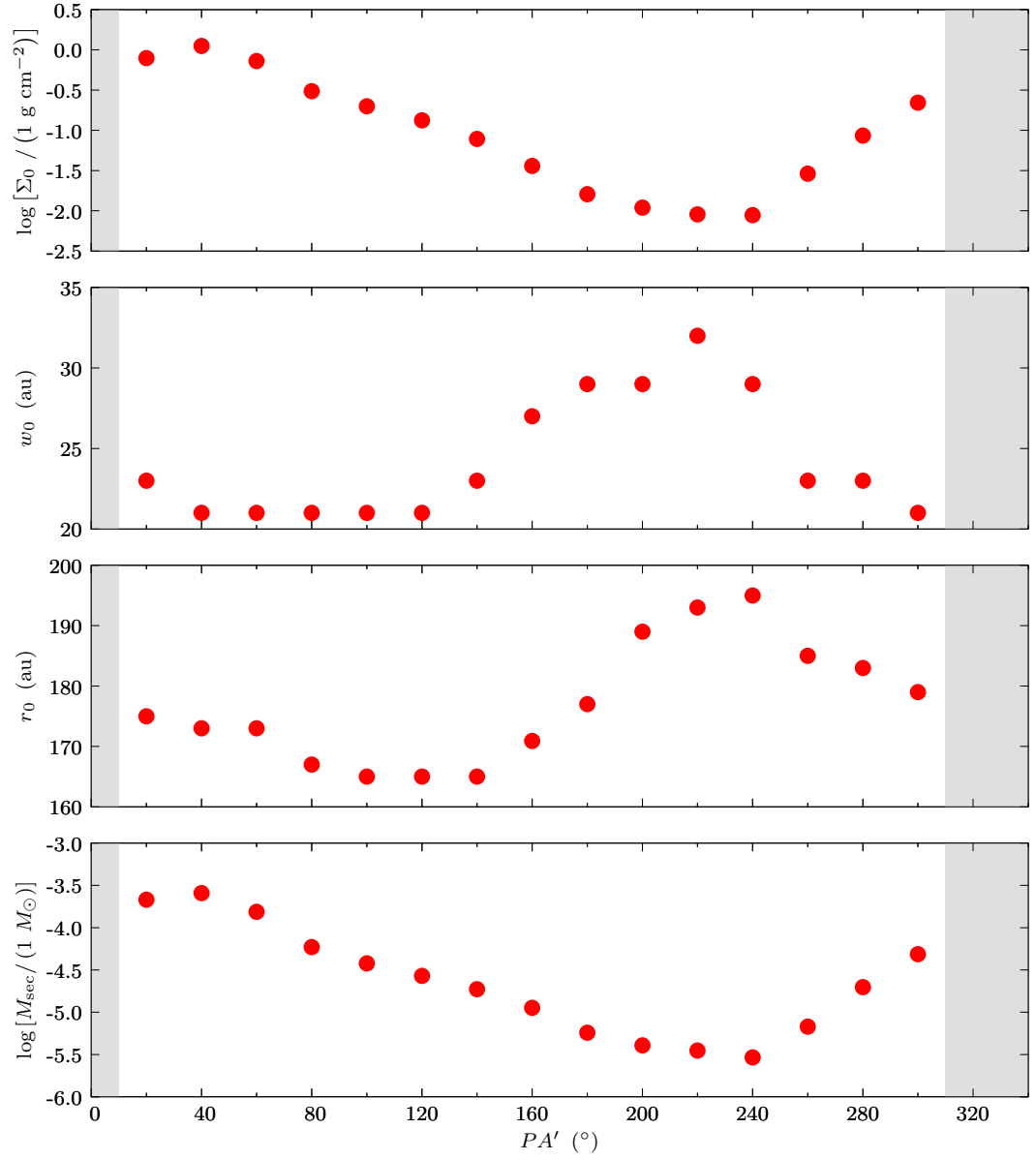


Figure 4.2: The best-fit parameters, Σ_0 , w_0 , r_0 , and M_{sec} , distributions along the PA' direction, derived using the conventional opacity for the compact dust model. The gray shaded portions indicate the PA' sectors where the radial profiles cannot be reproduced by the model.

Table 4.1: Derived best-fit values using the conventional model for dust opacity.

PA'	Σ_0 (g cm^{-2})	w_0 (au)	r_0 (au)	M_{sec} ($M_{\odot}$)	ΔI_0^* ($\times I_{0,\text{obs}}^*$)	Δw_0^* (au)	Δr_0^* (au)
$10^\circ - 30^\circ$	7.89×10^{-1}	23	175	2.1×10^{-4}	-1.3×10^{-5}	+0.8	-0.5
$30^\circ - 50^\circ$	1.12	21	173	2.6×10^{-4}	-2.9×10^{-5}	+0.3	-0.3
$50^\circ - 70^\circ$	7.28×10^{-1}	21	173	1.5×10^{-4}	-1.0×10^{-5}	-0.3	-0.5
$70^\circ - 90^\circ$	3.07×10^{-1}	21	167	5.9×10^{-5}	-2.5×10^{-5}	+0.1	-0.3
$90^\circ - 110^\circ$	2.00×10^{-1}	21	165	3.8×10^{-5}	-4.0×10^{-5}	-0.4	+0.8
$110^\circ - 130^\circ$	1.33×10^{-1}	23	165	2.7×10^{-5}	-1.6×10^{-5}	-0.2	-0.1
$130^\circ - 150^\circ$	7.83×10^{-2}	23	165	1.9×10^{-5}	-4.0×10^{-5}	+0.4	+0.6
$150^\circ - 170^\circ$	3.61×10^{-2}	27	171	1.1×10^{-5}	-1.1×10^{-5}	+0.2	-0.8
$170^\circ - 190^\circ$	1.61×10^{-2}	29	177	5.7×10^{-6}	-4.3×10^{-5}	+0.5	-0.0
$190^\circ - 210^\circ$	1.10×10^{-2}	29	189	4.1×10^{-6}	-4.5×10^{-5}	+0.5	-0.6
$210^\circ - 230^\circ$	9.05×10^{-3}	32	193	3.5×10^{-6}	-1.3×10^{-5}	-0.7	+0.7
$230^\circ - 250^\circ$	8.31×10^{-3}	32	195	3.0×10^{-6}	-4.6×10^{-5}	-0.7	+0.8
$250^\circ - 270^\circ$	2.89×10^{-2}	23	185	6.8×10^{-6}	-1.7×10^{-5}	-0.4	+0.1
$270^\circ - 290^\circ$	8.60×10^{-2}	23	183	2.0×10^{-5}	-3.6×10^{-5}	+0.2	-0.0
$290^\circ - 310^\circ$	2.21×10^{-1}	23	179	4.9×10^{-5}	-1.5×10^{-5}	+0.3	+0.1
$^\dagger 310^\circ - 330^\circ$	1.26	21	179	3.0×10^{-4}	(-5.7×10^{-2})	(-2.9)	+0.9
$^\dagger 330^\circ - 350^\circ$	1.26	21	177	3.2×10^{-4}	(-1.6×10^{-1})	(-1.2)	-0.4
$^\dagger 350^\circ - 10^\circ$	1.26	21	173	3.2×10^{-4}	(-3.4×10^{-2})	+0.7	+1.0

[†] These PA' sectors cannot be reproduced using the conventional values for dust scattering opacity (refer Figure 3.2); the (Σ_0, w_0, r_0) values listed here are for reference purpose only. The parenthesized parameters are those that do not fulfill the criteria in Equation (3.26). In $PA' = 350^\circ - 10^\circ$, only ΔI_0^* that does not meet the criteria, and is only by a slight margin.

4.2 The northwest region of the disk

The sectors in $PA' = 310^\circ - 10^\circ$ are located in the northwest region of the disk. Two problems are encountered in reproducing the radial intensity profiles in this region:

- (1) The highest intensity that can be achieved from the disk model is still lower than the observed intensity in $PA' = 310^\circ - 10^\circ$.
- (2) The radial intensity profiles of the model are wider than the profiles in $PA' = 310^\circ - 350^\circ$, even with the narrowest model disk width applied.

The reasons are discussed next.

4.2.1 Lower intensity in the model

The first problem can be identified from the fit values for $PA' = 310^\circ - 10^\circ$ listed in Table 4.1; even at $\Sigma_0 = 1.26 \text{ g cm}^{-2}$, an optically thick disk of $\tau_{\text{eff}} \approx 12$, the model peak intensities are still lower than the observed intensities. In particular, I_0^* is 16% lower than $I_{0,\text{obs}}^*$ in $PA' = 330^\circ - 350^\circ$. The consequence comes from the non-linear relation between Σ_0 and I_0 (or I_0^*) when the disk model is optically thick, as demonstrated in Figure 4.3. In

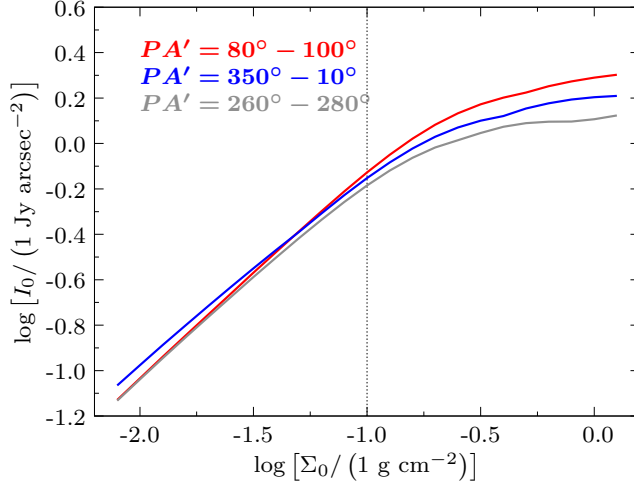


Figure 4.3: The peak intensity I'_0 achievable in $PA' = 80^\circ - 100^\circ$ (the far side, red plots), $PA' = 350^\circ - 10^\circ$ (the major axis, blue plots), and $PA' = 260^\circ - 280^\circ$ (the near side, gray plots), regardless of r' . The I_0 values are values before beam convolution. In the analysis, w_0 and r_0 are fixed at 27 au and 175 au, respectively. The vertical, black dotted line denotes the Σ_0 value where $\tau_{\text{eff}} = 1$.

the figure, the model peak intensity before beam convolution, I_0 , is plotted against Σ_0 , with constant $w_0 = 27$ au and $r_0 = 175$ au. The peak intensity in three sectors, $PA' = 80^\circ - 100^\circ$, $350^\circ - 10^\circ$, and $260^\circ - 280^\circ$, are studied; these sectors represent the far side, the major axis, and the near side of the disk, respectively. Keeping in mind that $\tau_{\text{eff}} \approx 1$ when $\Sigma_0 = 0.1 \text{ g cm}^{-2}$, the behavior of I_0 on both translucent and opaque disk models is inspected.

In $\Sigma_0 < 0.1 \text{ g cm}^{-2}$, I_0 is roughly proportional to Σ_0 . The I_0 values in $PA' = 80^\circ - 100^\circ$ and $PA' = 260^\circ - 280^\circ$ are the same in this $\tau_{\text{eff}} < 1$ regime, because in these regions the optical thicknesses in the line of sight, τ_{los} (see Section 3.4), are the same. The region in $PA' = 350^\circ - 10^\circ$ is the brightest among the sectors, since under the axisymmetric, inclined disk geometry τ_{los} towards the disk major axis is the largest. These circumstances have been recognized from Figure 3.7a.

In $\Sigma_0 > 0.1 \text{ g cm}^{-2}$ or equivalently $\tau_{\text{eff}} > 1$, the slope is shallower for a higher Σ_0 , an evidence showing that the addition of Σ_0 no longer increases I_0 proportionally. Consequently I_0 is approaching a limiting value, which I term it as the I_0 ceiling. The ceiling is highest on the far side, followed by the major axis, and last, on the near side. The results are in good agreement with the optically thick disk model shown in Figure 3.7b, and the ceiling reflects the temperature of the disk photosphere, or more precisely the source function S_ν at the surface where $\tau_{\text{los}} = 1$. As discussed in Section 3.3.2, the inclined, opaque disk model posts a geometry that only the hot inner wall on the far side can be observed, hence the I_0 ceiling in $PA' = 80^\circ - 100^\circ$ is the highest. On the other hand, the hot inner wall is well hidden from the line of sight in $PA' = 260^\circ - 280^\circ$, leaving only a photosphere of a lower temperature that can be observed. The sectors in $PA' = 310^\circ - 10^\circ$ are located in the near side of the disk, and most of their intensities are contributed from the colder region of the disk as the inner wall is partially or fully hidden from sight. It is concluded that, once the model intensity has reached a ceiling much lower than the $I_{0,\text{obs}}^*$ values in $PA' = 310^\circ - 10^\circ$, the insufficient amount of intensity cannot simply be covered by just further increasing Σ_0 .

4.2.2 Wider radial profiles in the model

Referring to Equation (3.26b), the negative Δw_0^* values in $PA' = 310^\circ - 350^\circ$ in Table 4.1 means that the radial width of the intensity profiles are wider in the model than the observed. In $PA' = 310^\circ - 330^\circ$, the difference between w_0^* and $w_{0,\text{obs}}^*$ is about as high as 6% even with the narrowest parameter setting at $w_0 = 21$ au.

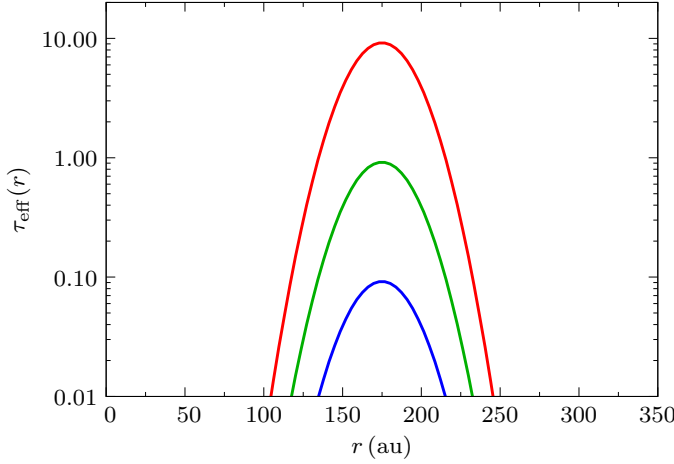


Figure 4.4: The optical thickness, τ , plotted as a function of the radius from the star, r .

The disk models attempted to reproduce the profiles in the northwest region are opaque, i.e., $\tau_{\text{eff}} \gg 1$. From its definition in Equation (3.33), in the radial direction τ_{los} will follow a Gaussian distribution as $\Sigma(r)$, the dust surface density defined in Equation (3.2). When $\Sigma_0 > 0.1 \text{ g cm}^{-2}$ or $\tau_{\text{eff}} > 1$, the intensity profile is significantly broadened in the radial direction because the intensity becomes insensitive to the increase in Σ_0 . As a consequence, the radial extent of the disk photosphere, i.e., the area in which $\tau_{\text{los}} = 1$, becomes wider in the increasing Σ_0 , and the intensity profile in the radial direction becomes saturated even before the beam convolution. The situation is exhibited in Figure 3.7, in which the higher Σ_0 disk model is more radially extended. We have seen that the intensity I_0 is already hitting a ceiling in the opaque disk, therefore using smaller w_0 setting will not resolve the Δw_0^* criterion in $PA' = 310^\circ - 350^\circ$.

In summary, the conventional values of dust opacity as depicted in Figure 3.2 cannot reproduce the radial intensity profiles in $PA' = 310^\circ - 10^\circ$ due to the low intensity ceiling compared to the observation and the broadening of the intensity profile when the disk model is opaque.

4.3 Uncertainty of the best-fit values

The best-fit (Σ_0, w_0, r_0) for the PA' sectors cannot be strictly constrained because of the insufficient angular resolution (≈ 60 au in FWHM). A large uncertainty of the best-fit values, especially of Σ_0 , in the optically thick region is expected because the intensity becomes insensitive to the increase in dust surface density and subsequently leads to the broadening of the radial profiles, as mentioned in Section 4.2. Here, we inspect the uncertainties of the best-fit values in the optically thin and optically thick sectors separately. As before, the transparency of each sectors is categorized by its effective optical thickness τ_{eff} ; excluding the northwest region of the disk, the sectors in $PA' = 130^\circ - 290^\circ$ are considered to be optically

Table 4.2: Fit values for $PA' = 230^\circ - 250^\circ$.

Model parameters				Results						
Σ_0 (g cm ⁻²)	w_0 (au)	r_0 (au)	$\Sigma_0 w_0$ (g cm ⁻² au)	M_{sec} ($M_\odot$)	I_0^* (au)	w_0^* (au)	r_0^* (au)	ΔI_0^* ($\times I_{0,\text{obs}}^*$)	Δw_0^* (au)	Δr_0^* (au)
8.31×10^{-3}	32	195	0.27	3.0×10^{-6}	0.05	52.3	173.3	-4.6×10^{-5}	-0.7	+0.8
8.85×10^{-3}	29	195	0.26	2.9×10^{-6}	0.05	50.8	173.9	-1.7×10^{-5}	+0.8	+0.3

Table 4.3: Fit values for $PA' = 30^\circ - 50^\circ$.

Model parameters				Results						
Σ_0 (g cm ⁻²)	w_0 (au)	r_0 (au)	$\Sigma_0 w_0$ (g cm ⁻² au)	M_{sec} ($M_\odot$)	I_0^* (au)	w_0^* (au)	r_0^* (au)	ΔI_0^* ($\times I_{0,\text{obs}}^*$)	Δw_0^* (au)	Δr_0^* (au)
1.12	21	173	23.52	2.6×10^{-5}	1.25	50.7	152.6	-2.9×10^{-5}	+0.3	-0.3
8.99×10^{-1}	23	173	20.68	2.3×10^{-5}	1.25	51.7	152.1	-1.8×10^{-5}	-0.7	+0.2

thin as $\Sigma_0 < 0.1 \text{ g cm}^{-2}$, while the sectors in $PA' = 10^\circ - 130^\circ$ and $PA' = 290^\circ - 310^\circ$ are optically thick for $\Sigma_0 > 0.1 \text{ g cm}^{-2}$. Here, I present two case studies for the uncertainties by using the radial intensity profiles in $PA' = 30^\circ - 50^\circ$ and $PA' = 230^\circ - 250^\circ$, which represent the translucent and the opaque limits, respectively. The uncertainty comes from the tolerance range of the criteria in Equation (3.26), and it will be investigated based on two parameters, $\Sigma_0 w_0$ and M_{sec} .

In the regime of effectively optically thin and constant temperature,

$$I_0^* \propto M_{\text{sec}} \propto \Sigma_0 w_0, \quad (4.1)$$

i.e., the peak intensity is proportional to the dust mass in the sector, which is determined by the product of Σ_0 and w_0 . Treating Σ_0 in Equation (4.1) as the bound variable, possible w_0 that will fit the radial profiles is searched, meanwhile fulfilling other criteria in Equation (3.26). Two set of results, each with w_0 values of 32 au and 29 au, for $PA' = 230^\circ - 250^\circ$ are listed in Table 4.2. Both sets satisfy the criteria ($\Delta I_0^*, \Delta w_0^*, \Delta r_0^*$), although they are different by $\sim 10\%$ in w_0 as well as in Σ_0 . The derived M_{sec} values, on the other hand, differ by less than 5%; the estimated masses are $3.0 \times 10^{-6} M_\odot$ and $2.9 \times 10^{-6} M_\odot$. In terms of $\Sigma_0 w_0$ the difference is also only about 5%. It is concluded that, for the optically thin sectors the uncertainty of the best-fit (Σ_0, w_0, r_0) is $\sim \pm 10\%$, while for the derived M_{sec} it is as low as $\pm 5\%$.

Table 4.4: Derived best-fit parameters and comparison with those by Muto et al. (2015).

Parameter	This work		[†] Muto et al. (2015)	
	$PA' = 30^\circ - 50^\circ$	$PA' = 230^\circ - 250^\circ$	$PA' = 30^\circ - 50^\circ$	$PA' = 230^\circ - 250^\circ$
Σ_0 (g cm^{-2})	1.12	8.31×10^{-3}	0.6	8.45×10^{-3}
w_0 (au)	21	32	27	34
r_0 (au)	173	195	173	196
Σ_0 ratio	$\frac{1.12}{8.31 \times 10^{-3}} = 135$		$\frac{0.6}{8.45 \times 10^{-3}} = 71$	

[†] $PA' = 30^\circ - 50^\circ$ and $PA' = 230^\circ - 250^\circ$ are referred as the north and the south sectors in Muto et al. (2015).

The results of the exact analysis for the optically thick $PA' = 30^\circ - 50^\circ$ are listed in Table 4.3. In terms of M_{sec} and $\Sigma_0 w_0$, as well as w_0 , the difference between the two sets is less than 15%, although in Σ_0 it reaches as high as 20%. This implies that Equation (4.1) breaks down when the intensity is approaching the I_0 ceiling, the point where the intensity gets insensitive to Σ_0 . The large error range of Σ_0 also explains the discrepancy between the results derived by us and by Muto et al. (2015), which are compared in Table 4.4. The derived parameters in $PA' = 230^\circ - 250^\circ$ are similar, but the Σ_0 value in $PA' = 30^\circ - 50^\circ$ is estimated to be larger than Muto et al. (2015) which lead to the almost twofold increase in the Σ_0 ratio between the sectors. Consistent results can be obtained if the tolerance range of the criteria in Equation (3.26) is relaxed to follow that of Muto et al. (2015), since a wider configuration of Σ_0 and r_0 will meet the criteria. The (Σ_0, w_0, r_0) values in the optically thick sectors are therefore loosely constrained, and the derived Σ_0 values contain at least an error of a factor of ~ 2 . Observations with a higher angular resolution, or at a longer

wavelength so that the continuum emission is less opaque, are required in order to disentangle the degeneracy between Σ_0 and w_0 as shown in [Equation \(4.1\)](#).

Chapter summary

1. The modeling results show that the derived dust surface density is in good agreement with the observed intensity of the dust continuum emission.
2. The emission in the northwest region of the disk, $PA' = 310^\circ - 10^\circ$, cannot be reproduced by the disk models because of the heavy scattering that lowers the model intensity and blurs the disk image.
3. The uncertainties in the optically thick northern region can be as high as a factor ~ 2 , because the increase of model intensity becomes insensitive to the increase of dust surface density when $\tau_{\text{eff}} > 1$.

Chapter 5

Discussions

In this chapter, I introduce a different opacity model by reducing the model scattering opacity in order to approach the problems encountered when modeling the northwest region of the disk in $PA' = 310^\circ - 10^\circ$, and I compare the new model to the opacity model used thus far. Later in the chapter, I will discuss the dependence of the model intensity on the azimuthal direction and the scattering opacity on the standpoint of the disk model.

5.1 Reducing the scattering opacity of the dust grains

Table 5.1: Derived best-fit values using the reduced-scattering model.

PA'	Σ_0 (g cm^{-2})	w_0 (au)	r_0 (au)	M_{sec} ($M_\odot$)	ΔI_0^* ($\times I_{0,\text{obs}}^*$)	Δw_0^* (au)	Δr_0^* (au)
$10^\circ - 30^\circ$	2.76×10^{-1}	31	173	1.0×10^{-4}	-4.0×10^{-5}	+0.9	-0.0
$30^\circ - 50^\circ$	3.34×10^{-1}	31	173	1.1×10^{-4}	-2.6×10^{-5}	-0.6	-0.9
$50^\circ - 70^\circ$	3.33×10^{-1}	29	173	9.8×10^{-5}	-2.7×10^{-5}	-0.8	-0.5
$70^\circ - 90^\circ$	2.46×10^{-1}	27	169	6.1×10^{-5}	-2.2×10^{-5}	-0.5	-0.6
$90^\circ - 110^\circ$	1.84×10^{-1}	23	167	3.9×10^{-5}	-3.1×10^{-5}	+0.0	-0.9
$110^\circ - 130^\circ$	1.24×10^{-1}	23	165	2.8×10^{-5}	-2.8×10^{-5}	+0.1	+0.2
$130^\circ - 150^\circ$	6.94×10^{-2}	27	167	2.0×10^{-5}	-2.7×10^{-5}	-0.7	-0.7
$150^\circ - 170^\circ$	3.32×10^{-2}	29	171	1.1×10^{-5}	-1.9×10^{-5}	-0.2	-0.9
$170^\circ - 190^\circ$	1.51×10^{-2}	31	177	5.7×10^{-6}	-1.0×10^{-5}	-0.4	-0.5
$190^\circ - 210^\circ$	1.07×10^{-2}	29	187	3.9×10^{-6}	-9.1×10^{-6}	+0.7	+0.6
$210^\circ - 230^\circ$	8.97×10^{-3}	32	193	3.5×10^{-6}	-3.5×10^{-5}	-0.5	-0.2
$230^\circ - 250^\circ$	8.28×10^{-3}	32	195	3.0×10^{-6}	-1.5×10^{-5}	-0.6	+0.1
$250^\circ - 270^\circ$	2.80×10^{-2}	23	185	6.5×10^{-6}	-4.4×10^{-5}	+0.1	-0.3
$270^\circ - 290^\circ$	7.26×10^{-2}	27	183	2.0×10^{-5}	-7.5×10^{-7}	-0.3	+0.9
$290^\circ - 310^\circ$	1.46×10^{-1}	27	181	4.2×10^{-5}	-8.1×10^{-7}	-0.1	-0.6
$310^\circ - 330^\circ$	2.37×10^{-1}	29	177	7.7×10^{-5}	-1.1×10^{-5}	+0.0	+0.3
$330^\circ - 350^\circ$	2.91×10^{-1}	29	175	1.0×10^{-4}	-2.2×10^{-5}	+0.7	-0.4
$350^\circ - 10^\circ$	2.59×10^{-1}	31	173	9.6×10^{-5}	-2.2×10^{-5}	+0.6	-0.9

Figure 4.3 shows that I_0 depends on both Σ_0 and PA' , and it reaches a ceiling when

τ_{eff} exceeds unity. The low intensity ceiling is a consequence of the large scattering optical depth, which hindered the modeling in $PA' = 310^\circ - 10^\circ$ as discussed in [Section 4.2](#). The conventional properties of the compact dust grains are applied in this work for their simplicity, although their actual opacity can be highly uncertain. The scenario in which dust grains, those that are $\ll 1$ m in radius, growing by agglomeration of submicron monomers are favored theoretically. Such aggregates have different properties than that of the compact grains in terms of scattering, as has been discussed in [Section 1.3](#). As a tentative attempt, we reduce the scattering opacity as defined by [Equation \(3.5\)](#) in the model by 90% across the wavelengths. The reduced-scattering opacity can be considered as one that effectively reduces the scattering cross section of the grains, or one that reduces the $[1 - g(a)]$ coefficient that would imply a more forward scattering with a larger g , or the combined effect of both. The reduced opacity is shown as the blue dashed line in [Figure 3.2](#). At $\lambda_{\text{obs}} = 890 \mu\text{m}$, κ_s is reduced $2.62 \text{ cm}^2 \text{ g}^{-1}$, which comes near to the value of κ_a . The absorption opacity κ_a is kept the same, so now the dust opacity has a lower albedo η . Using this reduced κ_s model, I derive the dust distribution in all PA' sectors in the disk of HD 142527, starting from the radiative transfer of the disk model to the parameter search by following the exact procedure in [Section 3.3](#). The different dust opacity will lead to different modeling results, in particular the values of Σ_0 and w_0 , and hence M_{sec} as well. In the following, I denote the reduced κ_s model by “reduced-scattering model”, in contrast to the “conventional model” which uses the conventional opacity values of compact grains.

The modeling results using the reduced-scattering model are shown in [Figure 5.1](#) and in [Table 5.1](#). The radial intensity profiles in all sectors, including those in $PA' = 310^\circ - 10^\circ$, are successfully reproduced. A smaller Σ_0 is derived in $PA' = 30^\circ - 50^\circ$ (the brightest sector in the observed dust emission) although in $PA' = 230^\circ - 250^\circ$ (the faintest sector in the observed dust emission) the value remains similar to the one estimated by the conventional model; the difference in Σ_0 is reduced to about a factor of about 40, a value close to the contrast in the observed brightness between the two sectors. [Figure 5.2](#) compares the results of (Σ_0, w_0, r_0) and M_{sec} between the conventional and the reduces-scattering models. The results in $PA' = 130^\circ - 290^\circ$ are less affected by the change in κ_s because they are optically thin, i.e., $\tau_{\text{eff}} < 1$, even in the conventional model. The r_0 distribution remains similar along PA' , because the brightest emitting region in the radial direction depends on the projected amount of dust grains into the line of sight but not on the scattering opacity. Next, on the two significant outcomes that accompany the reduction in the scattering opacity. First, in $PA' = 310^\circ - 70^\circ$, we find the reduced-scattering model estimates an average Σ_0 of 0.3 g cm^{-2} ; it is smaller by more than half the values in $PA' = 10^\circ - 70^\circ$ derived by the conventional model, which has failed to reproduce the observed intensity in $PA' = 310^\circ - 10^\circ$ even with Σ_0 as large as 1.26 g cm^{-2} . The same observations also applies to the results of M_{sec} since it is proportional to Σ_0 . Second, we see an increase estimate of w_0 as high as 50% in the northern sectors. The details will be discussed in the following.

The presence of scattering causes the observed intensity to be lower than that of the blackbody radiation, by approximately $(1 - \eta)^{1/2}$ or equivalently $\epsilon^{1/2}$ (see [Footnote 5](#)). This is demonstrated in [Figure 5.3](#), the similar plot as [Figure 4.3](#) that shows the relation between I_0 and Σ_0 . As reference the analysis using the conventional model is also plotted in the same figure. The initial linear response of I_0 to Σ_0 eventually hits an upper end when the latter is sufficiently high, regardless of κ_s . The model peak intensity, however, becomes brighter

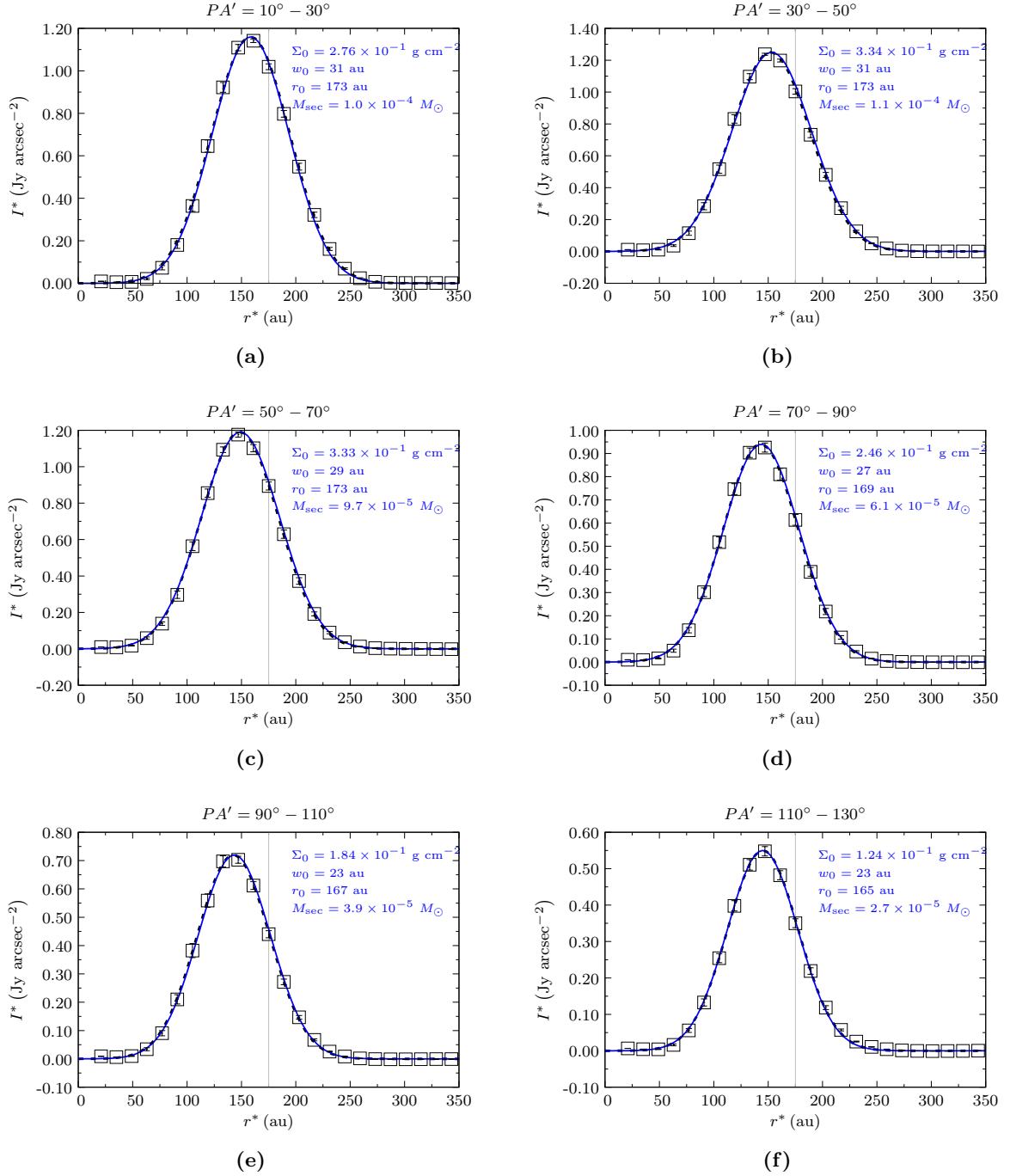


Figure 5.1: Same as Figure 4.1 but the blue solid lines are the modeling results using the reduced-scattering model. The best-fit parameters and the disk mass of the sector are written on the top right in each plot.

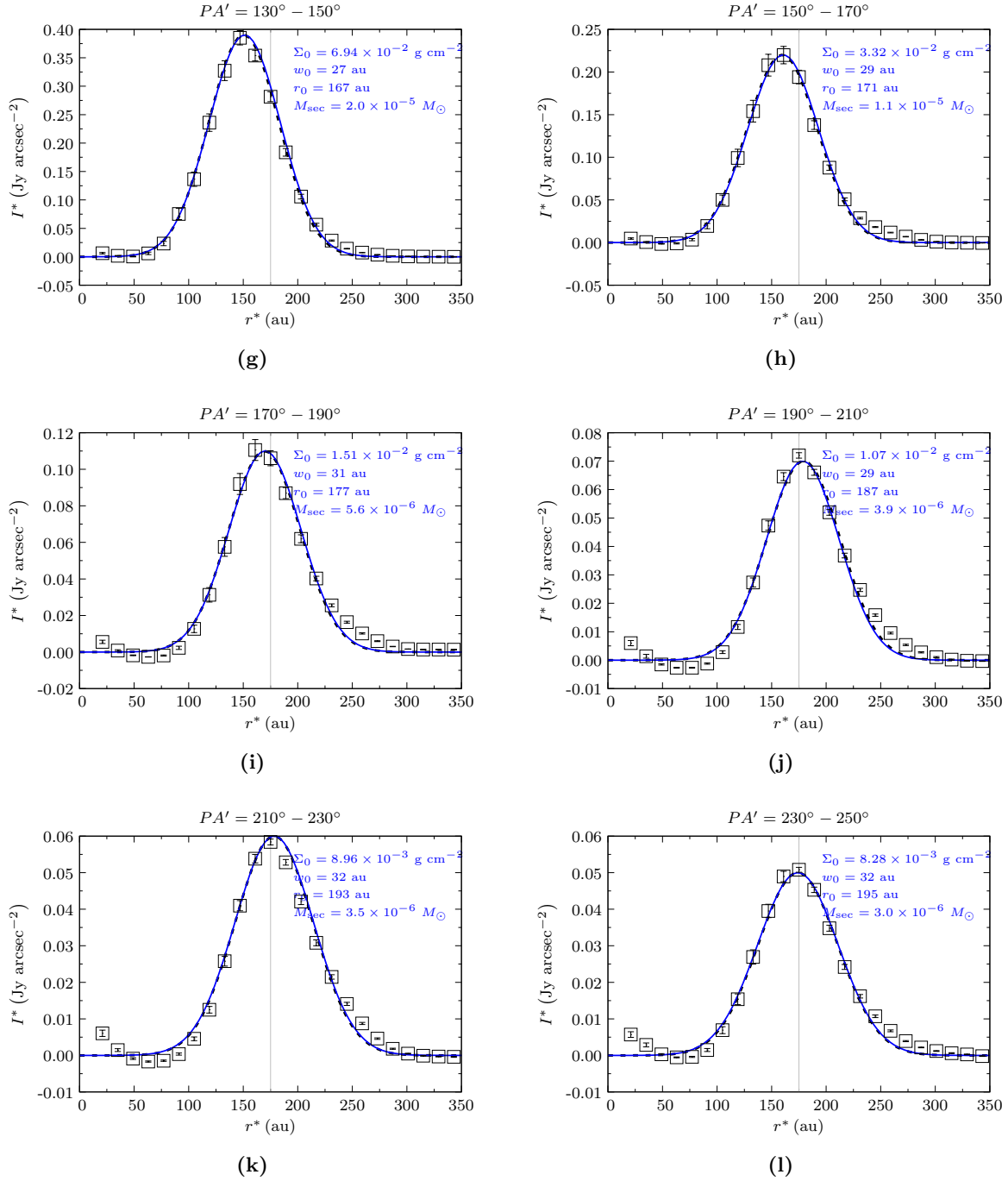


Figure 5.1: Continued.

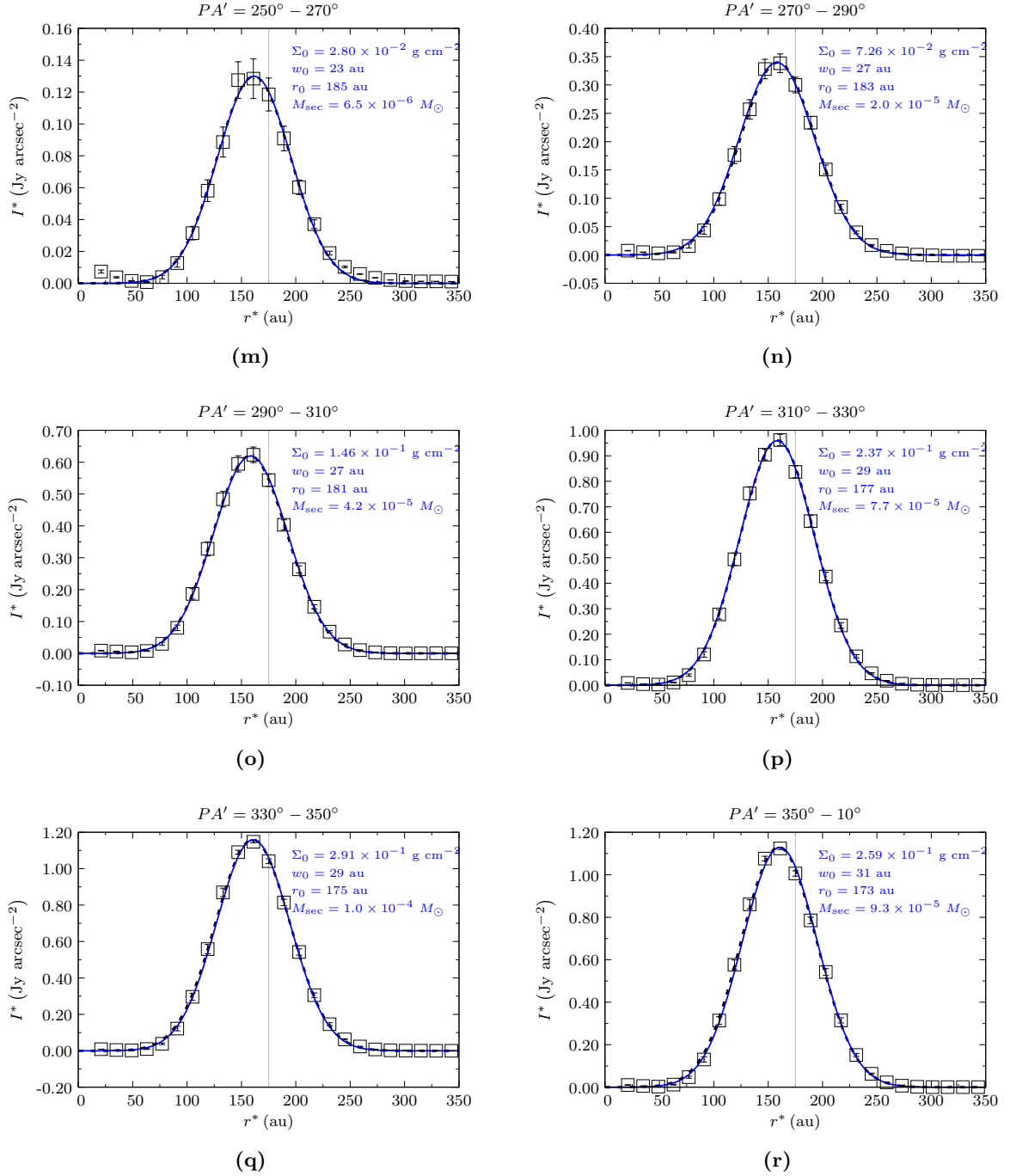


Figure 5.1: Continued. The radial profiles of $PA' = 310^\circ - 330^\circ$, $PA' = 330^\circ - 350^\circ$, and $PA' = 350^\circ - 010^\circ$ are reproduced well after reducing the scattering opacity in the model.

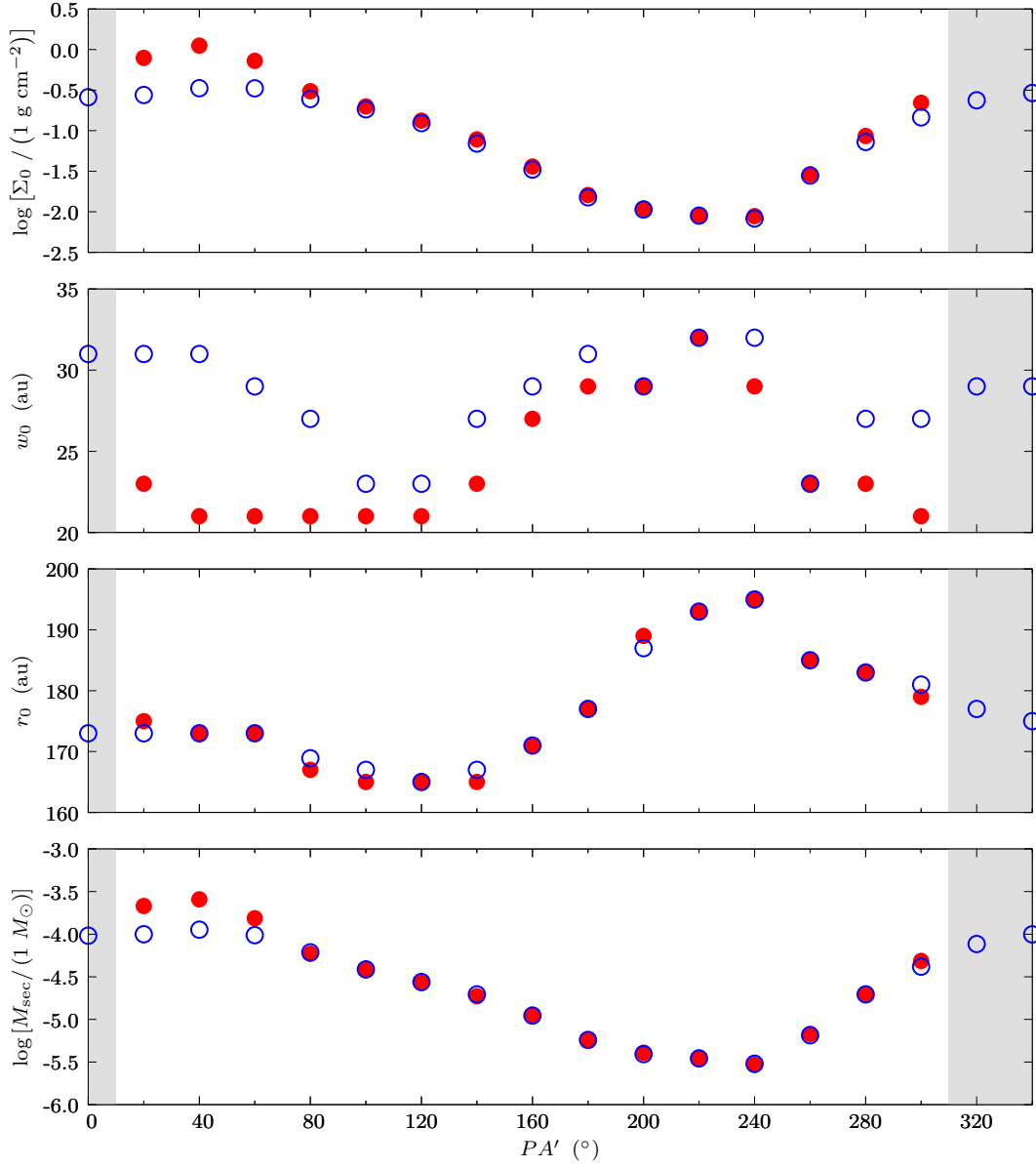


Figure 5.2: The best-fit parameters, Σ_0 , w_0 , r_0 , and M_{sec} , distributions along the PA' direction, derived using the conventional (red filled circles) and the reduced-scattering model (blue open circles). The gray shaded portions indicate the PA' sectors where the radial profiles cannot be reproduced by the conventional model.

over the range of Σ_0 and its ceiling is raised once κ_s is reduced. As a result, the reduced-scattering model estimates a lower Σ_0 for the northern sectors. In addition, by reducing κ_s the effective optical depth τ_{eff} approximates unity at $\Sigma_0 = 0.25 \text{ g cm}^{-2}$, compared to the lower $\Sigma_0 = 0.11 \text{ g cm}^{-2}$ in the conventional model. Consequently, the derived Σ_0 even in the brightest $PA' = 30^\circ - 50^\circ$ is effectively optically thick only by a margin. The uncertainty of the derived best-fit values in $PA' = 290^\circ - 130^\circ$, which are characterized as the optically thick sectors in [Section 4.3](#), is then well below the factor of ~ 2 in the case of the reduced-scattering

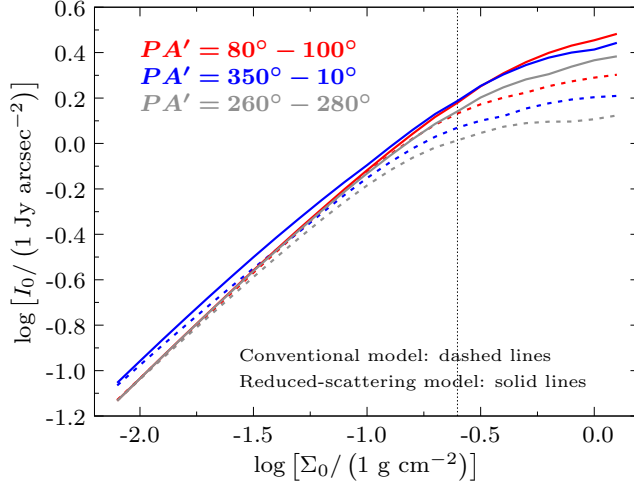


Figure 5.3: A similar plot to Figure 4.3; the dashed and solid lines denote the results using the conventional and reduced-scattering models, respectively. The I'_0 values are values before beam convolution. The vertical, black dotted line denotes the Σ_0 value where $\tau_{\text{eff}} = 1$ in the reduced-scattering model.

model.

The same discussions in Section 4.2.2 explain the larger estimation of the w_0 values in $PA' = 290^\circ - 130^\circ$. As derived by the conventional model, the effective optical thickness in these sectors exceed unity, which is the underlying reason of the broadening of the radial intensity profile. Qualitatively, if scattering is dominant the disk appears faint and indistinct, restricting only model of a small w_0 at a large Σ_0 to reproduce the radial intensity profiles. Reducing the scattering opacities sharpens the disk outline, i.e., the radial extent where τ_{los} equals unity is smaller, allowing a larger w_0 at a smaller Σ_0 to be a best-fit solution, as predicted by Equation (4.1).

As a conclusion, reducing the scattering opacity alters the results only in $PA' = 290^\circ - 130^\circ$. In particular, Σ_0 and M_{sec} are derived to be lower while w_0 is estimated to be wider. Contrarily, no significant changes are seen in $PA' = 130^\circ - 290^\circ$; the τ_{eff} values are below unity even before reducing κ_s so that the intensity is not much different between the conventional and reduced-scattering models.

5.2 Intensity dependence on scattering opacity and position angle

Revisiting Equation (3.34) and writing it in the coordinates along the line of sight z' , it reads

$$I(r', z') = (\kappa_a + \kappa_s) \int_{z'} \rho(r, z) S_\nu(r, z) e^{-\tau_{\text{los}}(z')} dz', \quad (5.1)$$

where $\tau_{\text{los}}(z')$ is the optical thickness measured in the in the line of sight of the observer, defined by Equation (3.33)

$$\tau_{\text{los}}(z') = - \int_{z'} \rho(\kappa_a + \kappa_s) dz', \quad (3.33 \text{ revisited})$$

It is shown that the observed intensity is a summation of $(\kappa_a + \kappa_s) \rho S_\nu \exp(-\tau_{\text{los}})$, the observable photon density, along the line of sight; the quantity denotes the emissivity per unit length with absorption and scattering taken into account through the attenuation factor $\exp(-\tau_{\text{los}})$.

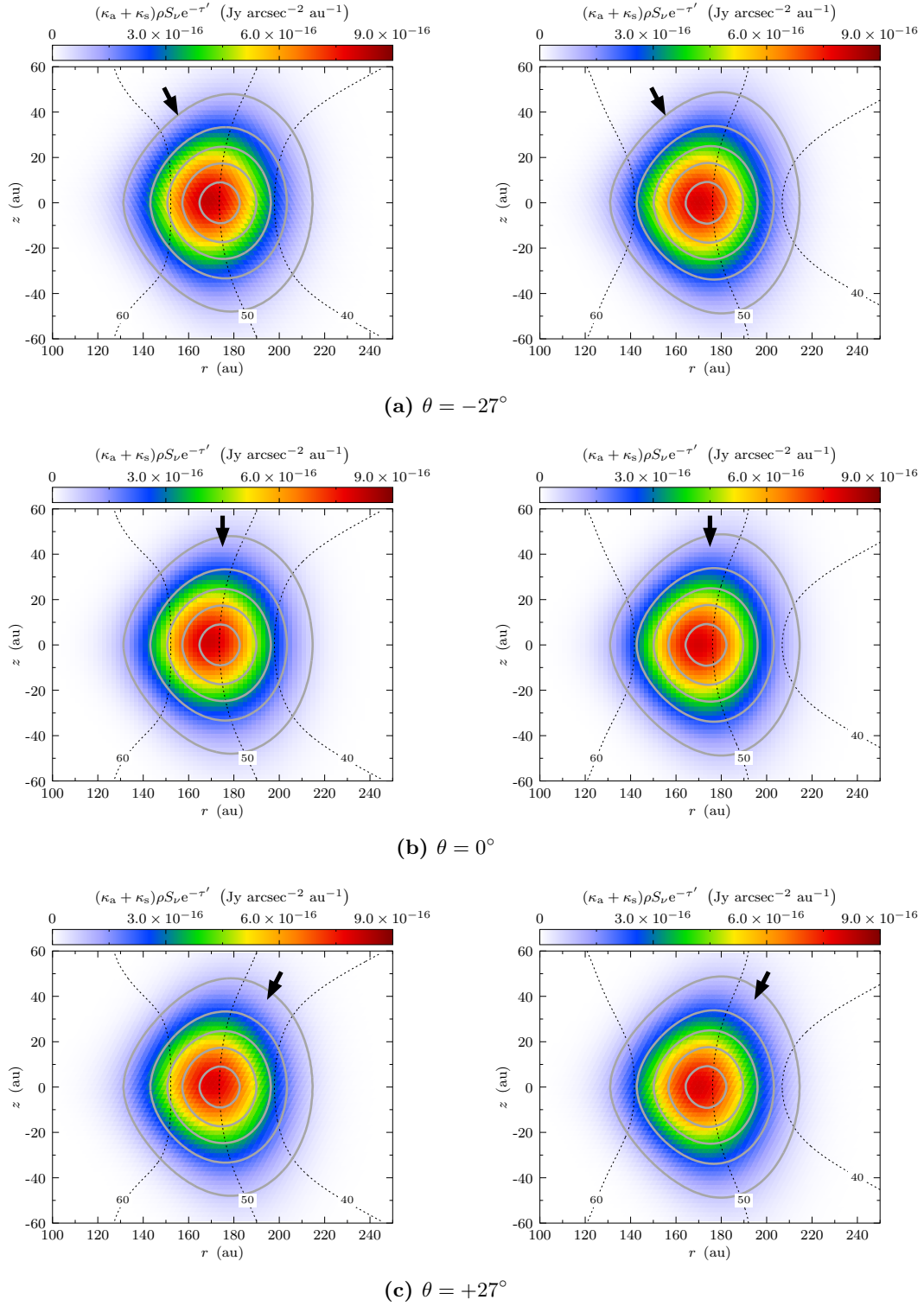


Figure 5.4: The $(\kappa_a + \kappa_s)\rho S_\nu \exp(-\tau')$ distributions of the conventional (left panels) and the reduced-scattering model (right panels), at a common $\Sigma_0 = 0.01 \text{ g cm}^{-2}$. The color scale is common for each panel. The top, middle, and bottom panels are the distributions at viewing angle $\theta = -27^\circ$, 0° , and $+27^\circ$, respectively, as indicated by the black arrows. The $\tau = 1$ and $\tau_{\text{eff}} = 1$ surfaces are not seen in this optically thin model. See text for details.

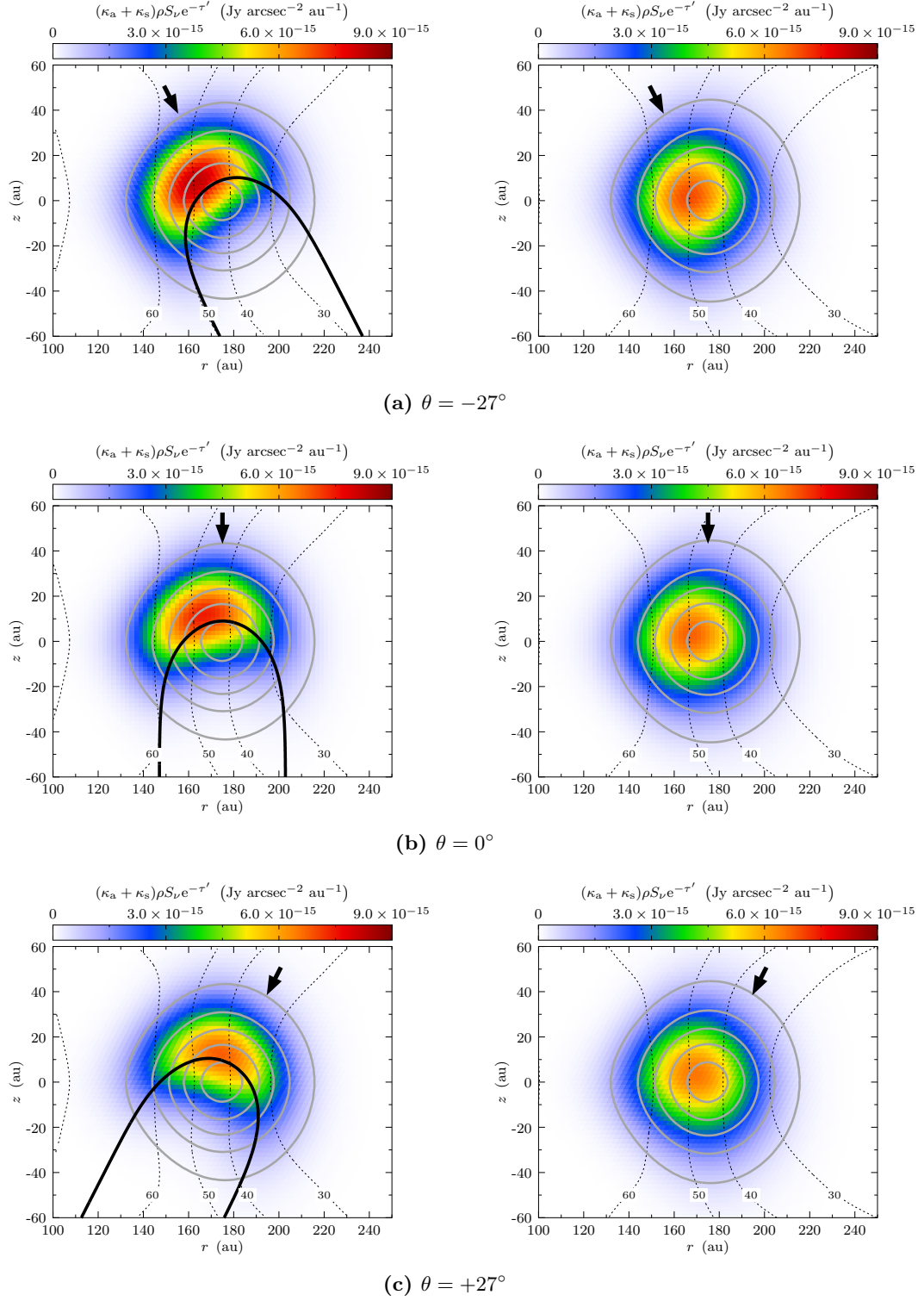


Figure 5.5: Same as Figure 5.4, for the case of $\Sigma_0 = 0.10 \text{ g cm}^{-2}$. The $\tau = 1$ surface appears in the disk of the conventional model, while $\tau_{\text{eff}} = 1$ surface is not seen in any of the models.

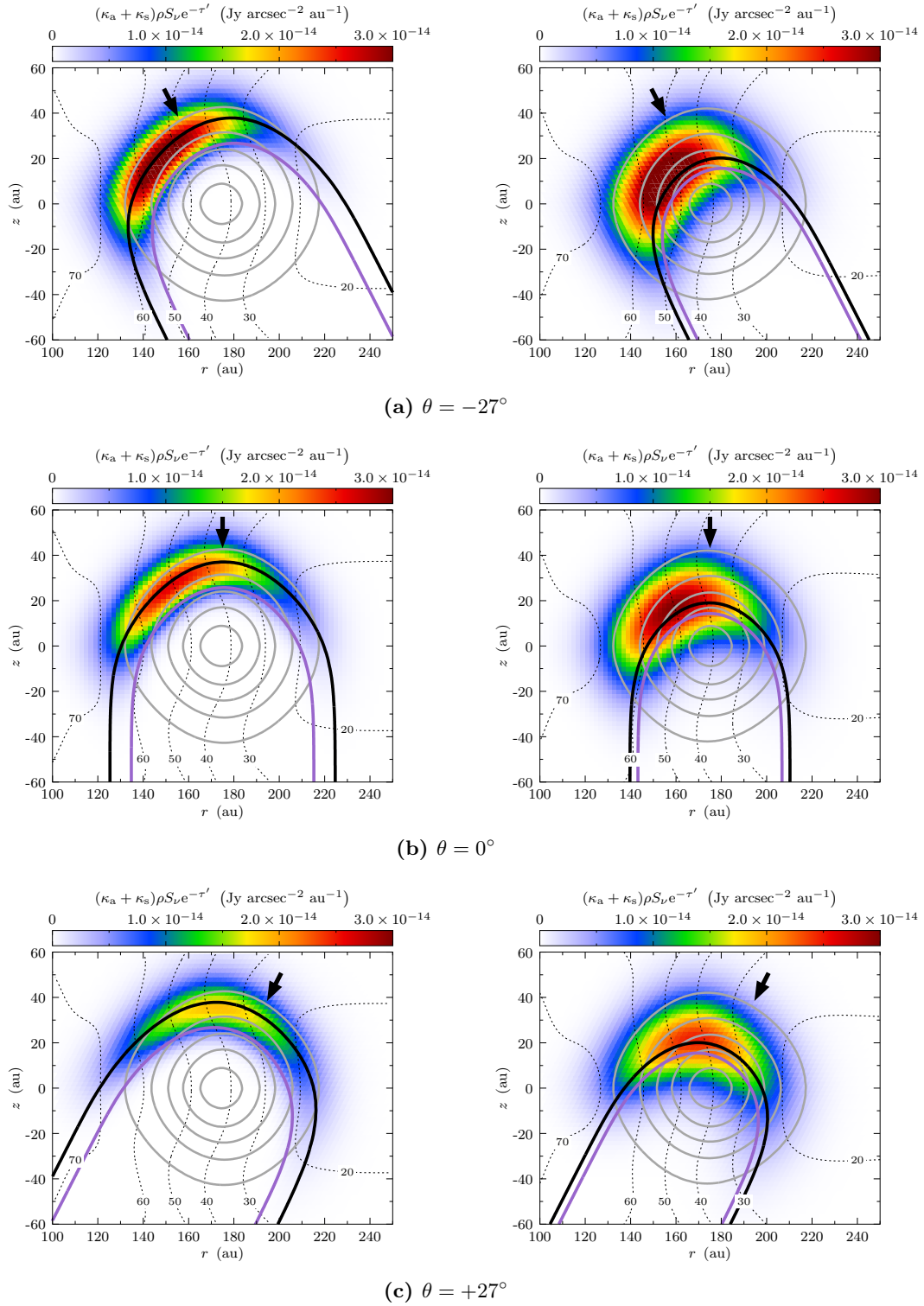


Figure 5.6: Same as Figure 5.4, for the case of $\Sigma_0 = 1.00 \text{ g cm}^{-2}$. Both the $\tau = 1$ and $\tau_{\text{eff}} = 1$ surfaces are seen in the disk, indicating the disk being optically thick.

In this section the observable photon densities of the conventional and the reduced-scattering models is investigated in order to understand quantitatively why by reducing the scattering opacity the ALMA observations in $PA' = 310^\circ - 10^\circ$ can be reproduce.

Figures 5.4 to 5.6 show the observable photon density, in units of $\text{Jy arcsec}^{-2} \text{ au}^{-1}$, of Σ_0 models at 0.01 g cm^{-2} , 0.10 g cm^{-2} , and 1.00 g cm^{-2} , respectively. The models are common at $w_0 = 27 \text{ au}$ and $r_0 = 175 \text{ au}$. The black dotted contours denote the temperature in units K. The gray solid contours are the dust spatial density drawn at $\rho(r, z) = 0.1, 0.3, 0.5, 0.7, 0.9$ of ρ_0 , the peak spatial density at $r = 175 \text{ au}$ and $z = 0 \text{ au}$, in the Σ_0 model. The line of sight is indicated by the black arrow; from top to bottom it is offset from the z -axis by an angle of $\theta = -27^\circ, 0^\circ$, and $+27^\circ$. Since the inclination of the disk is $i = 27^\circ$, the top panels correspond to $PA' = 90^\circ$ (the far side) while the bottom panels to $PA' = 270^\circ$ (the near side). The middle panels where $\theta = 0^\circ$ show the $(\kappa_a + \kappa_s)\rho S_\nu \exp(-\tau_{\text{los}})$ distribution of a face-on disk; they do not actually correspond to $PA' = 0^\circ$ because our line of sight does not lie in the (r, z) plane. However, the results can be regarded as a good substitute for the $PA' = 0^\circ$ case considering that the inclination angle is small. The results of the conventional model are shown in left panels while of the reduced-scattering are on the right panels.

We first look at the $\Sigma_0 = 0.01 \text{ g cm}^{-2}$ model. The effective optical depth of this model is well less than unity; it is about 0.09 and 0.04 in the conventional and the reduced-scattering model, respectively. In this translucent model, $(\kappa_a + \kappa_s)\rho S_\nu \exp(-\tau_{\text{los}})$ is high in the vicinity of $r = 175 \text{ au}$ and $w = 0 \text{ au}$, the densest region of the disk, and decreases outwards into the region of lower spatial density. In addition, the distribution is symmetric with respect to the disk midplane. Both the conventional and the reduced-scattering models are not only similar in the observable photon density, but the temperature as well, hence also the dust spatial density. The difference in the observable photon density between the two models, as well as among the line of sight angles θ within the same model, is small, and is only revealed by their results of I_0 in the lower Σ_0 limit plotted in Figure 5.3.

The $\Sigma_0 = 0.10 \text{ g cm}^{-2}$ model is optically thick at $\tau_{\text{eff}} \approx 1.00$ with the conventional opacity, but it is only $\tau_{\text{eff}} \approx 0.40$ in the reduced-scattering model. The black solid curve, seen only in the conventional model, delineates the location of $\tau_{\text{los}} = 1$, the photosphere of the disk. The difference between the models is now significant; unlike in the reduced-scattering model, in the conventional model the observable photon density peaks not in the densest region of the disk, but at the apex of the $\tau_{\text{los}} = 1$ curve. In addition, the photon density beyond the $\tau_{\text{los}} = 1$ surface (as seen from the observer) is highly attenuated as $\tau_{\text{los}} > 1$, so its distribution is no more symmetric with respect to the $z = 0$ plane. The photon density in the reduced-scattering model is departing from the midplane symmetric as well, and the peak value of $(\kappa_a + \kappa_s)\rho S_\nu \exp(-\tau_{\text{los}})$ is not as high as the other model. It is, however, the photon from a larger portion of the disk that reaches the observer makes the model brighter in the observed intensity. The dependence on the line of sight angle also becomes apparent at this optical thickness, which can be identified by the decrease in the peak value of the observable photon density in the order of $\theta = -27^\circ, 0^\circ$, and $+27^\circ$, which correspond to the far side, the major axis, and the near side of the disk, respectively.

The reduced-scattering model eventually gets optically thick with the increase of Σ_0 , and its effective optical thickness is $\tau_{\text{eff}} \approx 4$ at $\Sigma_0 = 1.00 \text{ g cm}^{-2}$. Still, the value is about half the value of the conventional model. At this Σ_0 the $\tau_{\text{los}} = 1$ photosphere is now seen in both the conventional and the reduced-scattering models, with the one in the former being notably

wider, verifying the broadening of the radial profiles discussed in [Section 4.2.2](#). Contrary to the reduced-scattering model, the photosphere in the conventional model is observed at a tenuous region of the disk, the dust spatial density of which is approximately 20% of ρ_0 . The portion of the observable photon is also confined in a narrow region in the vicinity of the photosphere, compared to the wider emitting region in the reduced-scattering model. The narrowing of the emitting area can be considered as the decrease in propagation speed caused by the dominant scattering. To examine this, I plot the $\tau_{\text{eff}} = 1$ location as the purple curve in the figures by scaling τ_{los} by a factor of $(1 - \eta)^{-1/2}$; the two are related by [Equation \(3.29\)](#). The observed photons come mainly from the region of $\tau_{\text{los}} = 1$, where τ_{eff} is still smaller than unity. This is because, while most of the photons are often emitted from the $\tau_{\text{eff}} = 1$ surface, they are scattered around $\tau_{\text{los}} = 1$ photosphere before reaching the observer. The time duration for the photons to travel from the former to the latter, as well as the albedo in the model, is reflected by the difference in physical distance between the two surfaces. When the albedo is high recurring scattering event effectively slows down the speed of the photons to escape the disk from the photosphere, thus resulting in the larger separation between the surfaces, and the narrower emitting area compared to the reduced-scattering model. We also notice that the difference among the angles θ , or the equivalent PA' , from the same model is stretched to a greater extent. To the observer, the temperature of the photosphere is the highest when $\theta = -27^\circ$, the lowest when $\theta = +27^\circ$; the former is the condition in which the hot inner wall is observed, while the latter is when the wall is hidden from sight.

As a conclusion, regardless of κ_s the $\tau_{\text{los}} = 1$ photosphere forms at the disk tenuous region when $\tau_{\text{eff}} > 1$, and it gets wider with increasing optical depth. At the same time, the area of the observable photon density is narrowed, although in the model with the higher κ_s the area will be more confined to the photosphere. In addition, the near side of the disk will hit a I_0 ceiling at a lower Σ_0 as it is the colder photosphere that contributes most of the observed intensity. These circumstances seen from the two-dimensional disk model confirm the difficulties in modeling the radial intensity profiles in the northwestern region of the disk, in $PA' = 310^\circ - 10^\circ$, by using the conventional scattering opacity.

The effects of scattering on the intensity is serious only when $\kappa_s > \kappa_a$. Further reduction in the scattering opacity will increase the intensity only by a little, thus a lower limit on the scattering opacity cannot be well determined. Nevertheless, the scattering opacity of the dust grains should be appreciable since the pattern of polarization in the disk at $\lambda = 890 \mu\text{m}$, recently revealed by ALMA, seems consistent with the case of self-scattering ([Kataoka et al., 2015](#); [Kataoka et al., 2016](#)).

5.3 Interpretation of the results

From [Figure 5.2](#) it is clear that the effect of reducing the scattering appears only in regions where the effective optical is larger than unity even with the reduced-scattering model. How are we to interpret the different modeling outcome? Some ideas are as follows.

- (1) The reduced-scattering model is the optimum model that describes the dusty disk.
- (2) The different results suggest that the optical properties of the grains vary spatially in the disk. This may corroborate with the scenario of vortex formation where different grain sizes distribute differently in the azimuthal direction.

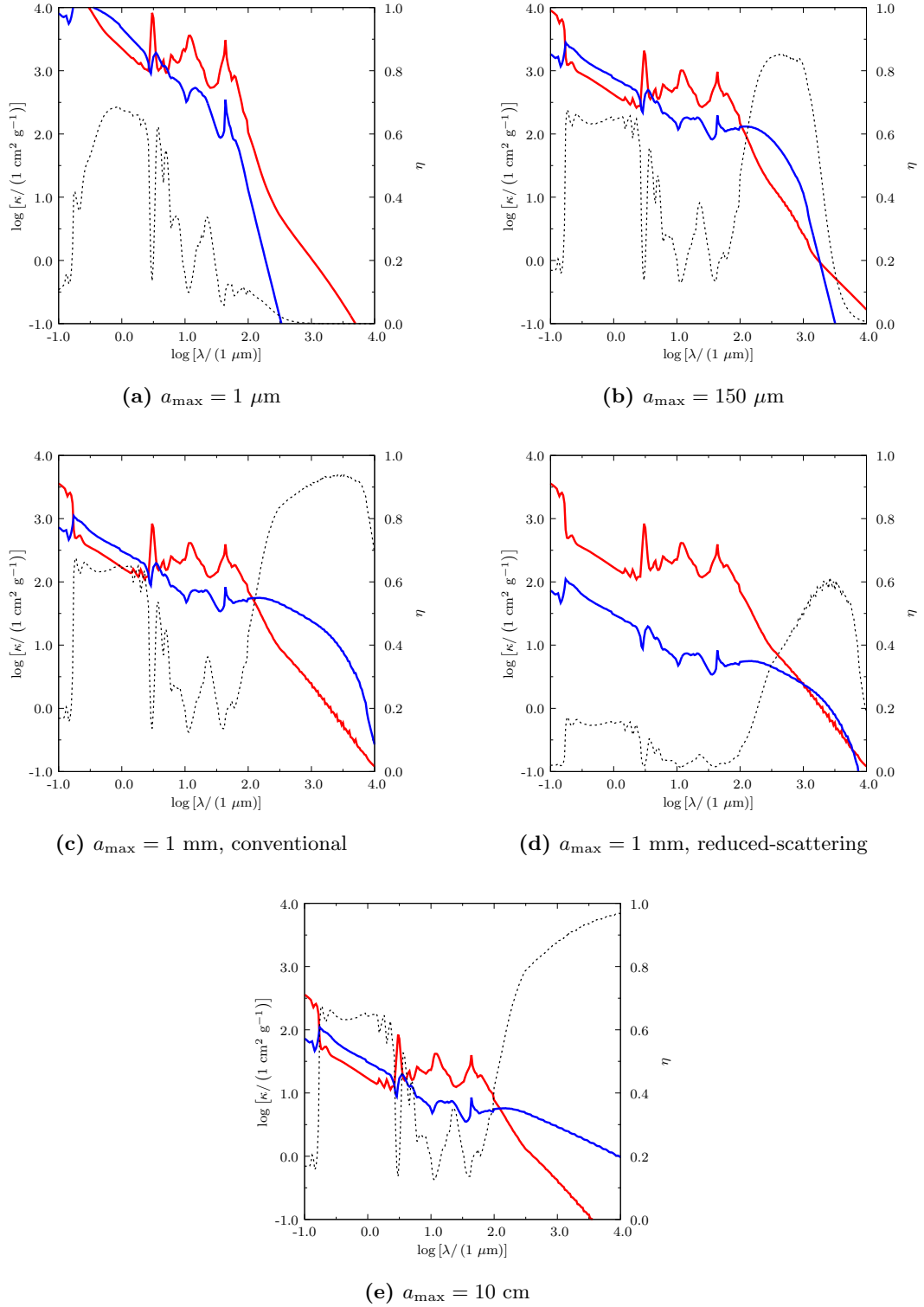


Figure 5.7: The absorption opacity (solid red line) and the scattering opacity (solid blue line) for compact dust grains following the power-law size distribution of $n(a) \propto a^{-3.5}$, for various cases of $a_{\max}$. Also plotted is the albedo, η , in dashed line, and its value is indicated by the right y -axis. The plots in (c) and (d) are the opacity for the conventional and reduced-scattering models, respectively.

- (3) The dust grains has been assumed to be compact in both opacity models, however, their modeling results may be considered as the difference in using a compact, spherical grains and an aggregate composed of submicron monomers.

The last interpretation is based on the fundamental properties of the dust grains themselves, where the assumption on the grains as compact spheres might be inappropriate. That being said, the composition and the volume filling factor of the monomers in the aggregate is still less well understood, and so are their scattering properties (Kataoka et al., 2014; Tazaki et al., 2016). A promising planet formation scenario that can avoid the radial drift barrier of planet formation is indeed one including the growth of dust grains by aggregating monomers (Kataoka et al., 2013); centimeter particles or meter-size bodies (the sizes which are most prone to drifting inward to the star as $St \sim 1$) can grow into planetesimals if they coagulate via gas compression and self-gravity compression. The planetesimals will then be the raw materials for planets formation. the model intensity will be lower than the observed due to the heavy scattering.

Next, we look into if changing $a_{\max}$ of the dust distribution will alter the results. In Figure 5.7, the opacity of compact grains of various $a_{\max}$ that follows the power-law size distribution of $n(a) \propto a^{-3.5}$ are plotted. Also plotted is the albedo as defined by Equation (3.24),

$$\eta \equiv \frac{\kappa_s}{\kappa_a + \kappa_s}, \quad (3.24)$$

for each $a_{\max}$ dust configuration. Other than $a_{\max}$ the properties of the dust grains are the same as the one of $a_{\max} = 1$ mm discussed in Section 3.2.2. The figure depicts that, even when the grain size is smaller (e.g., $a_{\max} = 150 \mu\text{m}$) or larger (e.g., $a_{\max} = 10$ cm), the scattering is still dominant at the submillimeter and millimeter wavelengths. When optically thick the intensity in the Rayleigh-Jeans regime will be lower than the blackbody emission by $(1 - \eta)^{-1/2}$, and since $\eta \sim 0.8$ for $a_{\max} \sim 100 \mu\text{m} - 10$ cm at the modeling wavelength $\lambda_{\text{obs}} = 890 \mu\text{m}$, decreasing or increasing $a_{\max}$ of the compact grains will likely lead to a similar conclusion: in the northwest region,

Although no firm conclusion can be made at this stage, this work suggests that the scattering of dust grains may be somehow lower than expected in the submillimeter and millimeter wavelengths, whose cause is most likely to be coming from the chemical composition and the structure of the grains.

5.4 Validity of the model

As mentioned at the beginning of Section 3.2, the two-dimensional axisymmetric model might not be able to describe the scattered light accurately in the crescent disk, especially when scattering is dominant. I discuss the validity of the axisymmetric disk by using Figure 5.6. In the figure, the difference between $\tau_{\text{los}} = 1$ and $\tau_{\text{eff}} = 1$ corresponds to the typical length travelled by a photon before escaping from the disk. Even when the albedo is high as in the conventional model, this length is approximately 10 au, much shorter than the arc length subtended by the 20° -sector at $r_{0,\text{obs}}^* \approx 160$ au which is approximately 56 au. This implies that the contribution of scattered radiation from other sectors is negligible, and the two-dimensional axisymmetric model is a good approximation to reproduce the asymmetry intensity distribution of the disk.

Chapter summary

1. In order to reproduce the dust continuum emission at $\lambda_{\text{obs}} = 890 \mu\text{m}$ in $PA' = 310^\circ - 10^\circ$ of the disk around HD 142527, the scattering opacity is reduced by 90% across the modeling wavelengths. This model is denoted as the reduced-scattering model, in contrast to the conventional model which has the conventional values for scattering opacity.
2. The reduced-scattering model estimates a lower Σ_0 but a higher w_0 for the northern region of the disk, which is marginally optically thick in the reduced-scattering model and is $\tau_{\text{eff}} \gg 1$ in the conventional model. The disparity in the derived values comes from the fact that, when optically thick, by reducing scattering the model intensity tends towards that of a blackbody, and its increase is only limited when the model reaches a higher Σ_0 compare to the conventional model. In addition, the smaller scattering results in a clearer image that will allow a larger w_0 model to be the best-fit model.
3. Inducing the inclination angle makes the model intensity to be depending on the disk azimuthal direction, although the disk model itself is axisymmetric.
4. By examining the emissivity in the two-dimensional disk model, it is seen that the difference between the two opacity models sets in only when $\tau_{\text{eff}} > 1$; compared to the reduced-scattering model, the conventional model has a narrower emitting region, thus overall appears to be darker.
5. The scattering opacity may be lower than expected. Future simulations that take the phase function, chemical composition, as well as the structural properties into full consideration are required to better understand their nature.

Chapter 6

Concluding remarks

6.1 Summary of the modeling results

This work derived the dust distribution of the crescent disk around HD 142527 by reproducing the observed radial intensity profiles of the continuum emission at $890\ \mu\text{m}$ obtained by ALMA during Cycle 0. Two opacity models are used in the modeling, where one of them has the scattering opacity reduced from its conventional values across the wavelength by 90%. The radial distribution of surface density is assumed to be a Gaussian function whose peak and radial width are denoted as Σ_0 and w_0 , respectively. The scattering opacity of dust grains is also taken into account. The radiative and hydrostatic equilibria in the disk are solved by the M1 method. The results are summarized as follows.

- (1) At first, the absorption opacity κ_a and the scattering opacity κ_s of the compact dust grains are adopted in the modeling. The composition of the grains is consistent with the solar elemental abundance and a power-law size distribution with the maximum radius of 1 mm. At the modeling wavelength $890\ \mu\text{m}$, κ_s is about 10 times larger than κ_a . With these conventional opacities the radial intensity profiles in the northwestern region of the disk cannot be reproduced, observation of which shows high intensity and is located in the near side of the disk. The model intensity in this region reaches a lower ceiling than the observed peak intensity due to heavy scattering.
- (2) When the scattering opacity is reduced to 10% from the conventional value, the observed intensity distributions are reproduced successfully in all the position angles, including those in the northwestern region. The best-fit values depend little on the scattering opacity in the southern region where the disk is optically thin. On the other hand, Σ_0 is derived to be $\sim 50\%$ smaller, while w_0 becomes $\sim 50\%$ wider in the optically thick northern region. The contrast in Σ_0 between $PA = 11^\circ - 31^\circ$ and $PA = 211^\circ - 231^\circ$, which are the brightest and the faintest regions in the dust continuum emission, respectively, is derived to be ≈ 40 , much smaller than the ratio for the case of conventional opacity ($\sim 70 - 130$).
- (3) Detailed inspection of the model shows that in the case of inclined, effectively optically thick disk, the temperature on the emitting surface depends on the position angle even if the disk is axisymmetric. As a result, the emergent peak intensity also varies azimuthally. The effects of reducing scattering set in when the disk model

is optically thick, where the area of emission in the disk becomes wider and thus results in a higher observed intensity.

As a conclusion, the scattering opacity of the dust grains may be somehow lower than that of the compact, homogeneous grains, and the assumption of compact sphere as the structure for the dust grains may also be inappropriate in the protoplanetary disks. Whether it is a cause of the chemical composition or the structure of the grains, or even the computational method, is uncertain, and it is foreseen that more simulations on the optical properties of grains and disk modeling works are required to understand the solid particles in protoplanetary disks.

6.2 Future work

In order to better constrain the surface density of the dust, as well as of the gas, multi-wavelength observations towards the protoplanetary disks will become essential as to eliminate the degeneracy among surface density, temperature, and opacity. Complemented with gas and dust emission modeling, the size distribution of the grains and their optical properties in the protoplanetary disks can also be examined with better accuracy (Tazzari et al., 2016). In addition, polarization observation and modeling will definitely provide even more stringent constraint on the disk properties. In this work the M1 method is used to solve the radiative transfer in the disk model; while the method is a good approximation it does not fully consider the phase function of the grains. Eventually a Monte Carlo based simulation is required to account for the scattering angle, but it will also come with a high computational cost.

Higher angular-resolution observations towards the disk around HD 142527 is certainly highly anticipated, however in the mean time by using the dust surface density derived from this work modeling of gas emission can be carried out. This is important in understanding the dynamics of the disk as the gas is presumably the major constituent of the disk.

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