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# Modeling of Protoplanetary Disks Based on Radmc-3D

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**Abstract.** From the early stages of star formation to the formation of planetary systems, stars are surrounded by a disk of material that changes in structure and properties as the stars and planets evolve. This disk of material is called the protoplanetary disk, which consists of a large amount of dust and gas, and with the formation of planetary systems, the protoplanetary disk further evolves into a debris disk. The structure of the protoplanetary disk is closely related to the growth of the planets in the disk, and its diversity contributes to the diversity of planetary systems, so the study of protoplanetary disks is of great significance to the understanding of planetary formation and evolution. In this paper, we introduce the evolution of protoplanetary disks and the theoretical methods needed to construct their models. The simulation process of protoplanetary disks is understood by applying the RADMC-3D software package. In addition, I we collected the physical parameters of HL Tauri from the literature, applied these parameters to RADMC-3D for simulation, and analyzed the results of the simulation. Meanwhile, this paper also introduces the important role of the new generation of radio interferometric arrays in the field of protoplanetary disk observation.

**Keywords:** protoplanetary disks; debris disks; RADMC3D; modeling; SKA

## 1. Introduction

Protoplanetary disks form during the process of star formation. Huge clouds of gas and dust collapse under their own gravity, with the center forming the protostar and the surrounding material rotating around the protostar, gradually forming a flat disk-like structure known as a protoplanetary disk.

The study of protoplanetary disks helps to understand how planets form from dust particles that gradually accumulate, shedding light on the birth of planets in our solar system and other stellar systems. The chemical composition and physical processes in protoplanetary disks may be relevant to the origin of life, providing clues to the search for extraterrestrial life. The study of protoplanetary disks promotes the cross-fertilization of astrophysics, hydrodynamics, chemistry and other disciplines, and promotes the development of theories and technologies in related fields.

The evolution of protoplanetary disks can be roughly divided into the molecular cloud collapse phase [1], protostellar phase [1,2], jet phase [1,2] and disk diffusion phase [1]. In the diffusion phase, the otherwise intact dust disk has been removed, leaving only the formed stars, planets, and some residual dust. There is a significant mass reduction in this phase compared to the previous phases, which manifests itself in the spectral energy distribution (SED) as a significant reduction of the infrared excess. At a specific radial location in the interior of the disk, a crack forms, dividing the disk into inner and outer parts. The material of the inner disk is accreted onto the star, thus creating a cavity in the overall system structure. The inner edge of the disk will be directly irradiated by the star, and the stellar wind and radiation from the young star will remove material from the outer disk [3,4,5]. When the gas inside the disk has been completely expelled, the remaining dusty disk is the periastron debris disk (Debris Disk).

A variety of structures in the periastron debris disk reflect traces of the planetary formation process, and by analyzing the data from these disks, it is possible to infer the number of planets, their orbital positions, and the types of planets that may be contained in the planetary system of the host star. The study of periastron debris disks not only helps to deepen our understanding of the future evolution of the solar system, but also provides an important scientific basis for the search for potentially human-habitable planets, i.e., habitats for life beyond Earth.

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During the evolution of periastron disks, tiny dust particles adhere to form irregular aggregates through Brownian motion and electrostatic forces, and are subsequently compressed into spherical particles. As the particles increase in size, they gradually separate from the gas and settle to the disk center plane and increase in density. After settling to the center plane, the particles drift radially inward at high speed. The probability of collision increases dramatically, and the outcome of the collision (adhesive growth or fragmentation) depends on the relative velocity and the nature of the particles. Under prolonged evolution, dust particles eventually aggregate into kilometer-sized stars. Stars continue to collide, forming the cores of Earth-like planets and gas giants. Gas giant planet cores rapidly accrete gas to form atmospheres before the disk is depleted of gas, while terrestrial planet cores continue to grow and take shape mainly by accreting the remaining dusty material during the debris disk phase after gas depletion [6].

With the development of observational techniques, astronomers have discovered nearly 4,000 exoplanets and have found debris disks around about 20% to 30% of main sequence stars in the solar neighborhood [7]. Observational techniques have undergone significant development over the past few decades, with the commissioning of the Infrared Astronomical Satellite IRAS in 1983, the Spitzer Space Telescope in 2003, the ALMA Radio Telescope Array in 2013, the Webb Space Telescope JWST in 2021, and the SKA Radio Array, which is due to be completed in the near future, providing higher spatial resolution direct imaging. To resolve these observations, many disk simulation software have been developed, such as RADMC-3D for radiative transfer simulation, ACE for collision simulation, and DMS for analyzing optically thin disk models. In this paper, we will mainly use RADMC-3D to simulate protoplanetary disks, study the effect of different parameters on the disk, and simulate and analyze the actual object HL Tauri.

## 2. Theory of Perihelion Disk Modeling

In order to study the properties of the dust distribution within the debris disk, detailed numerical simulations of the collisional cascades between dust particles are required. Specifically, the dynamical evolution of dust particles in 104 to 106 orbits is simulated taking into account the gravitational field of the central star, the gravitational uptake of the planets, the radiation pressure, and the stellar winds, and the equations of motion of the particles are accurately integrated numerically in order to capture their complex orbital behavior and interactions. The simulation methods have been continuously improved by previous authors, and several mainstream modeling theories are described below.

N-body code: tracks the trajectories of n dust particles by numerically integrating their equations of motion and stores their instantaneous positions and velocities. However, there is a fatal drawback that it cannot handle particles with a large range of masses and therefore cannot be used to accurately represent the dust distribution. [8]

ACE (Analysis of Collisional Evolution) code: because of the excessive number of debris disk particles, N-body simulations are no longer applicable, and a representation of particle distributions and collision statistics is used for the simulation. In order to reduce the amount of computation, the collision calculation groups similar particles into groups for computation, and the grouping methods are time-resolved method (A) and orbit-averaging method (B).Method A: Particles with close spatial distance and similar velocity vectors are categorized as super particles.Method B: Particles are grouped according to their orbits. Each group of particles is mapped to a predetermined elliptical (or hyperbolic) orbit, where the spatial distribution of the particles is assumed to be uniform over time. In this approach, the orbits of the particles are considered discrete and remain fixed throughout the simulation. This strategy of orbital grouping permits a simplified treatment of the dynamical behavior of a large number of particles, thus improving the computational efficiency while maintaining a certain level of accuracy.

The phase-space orientation angle parameter of the ACE is $\varpi \equiv \Omega + \omega$, denoting the longitude of the pericenter point = longitude of the ascending point + angle of circumference

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The evolution of the debris disk is depicted as a discrete distribution of matter represented by a four-dimensional lattice of (1) mass of the object m, (2) orbital pericenter point q, (3) eccentricity e, and (4) longitude of the pericenter point. Collisions between pairwise combinations of the grid may occur at up to two different points defined by the qs, es, and qs of the colliding objects. The collision speeds, rates and outcomes follow directly from . [9]

$\dot{n}_i$ denotes the phase space density at position x as a function of velocity v(x), q(x),e(x), and w(x)

$$\dot{n}(x) =- [\frac{\partial}{\partial q} n(x)\dot{q}(x) + \frac{\partial}{\partial e} n(x)\dot{e}(x) + \frac{\partial}{\partial \varpi} n(x)\dot{\varpi}(x)]$$

Integration of the above equation over time yields the discrete master equation:

$$\dot{n}_i = \sum_{jk} G_{ijk} n_j n_k - \sum_j L_{ij} n_i n_j + \sum_j T_{ij} n_j$$

where $\dot{n}_i$i is determined by the multi-index $i = (i_m, i_a, i_e, i_\varpi)$, the coefficients $G_{ijk}$ denote the gain (the specific rate at which an object of type i is formed in a collision between an object of types j and k), (the specific rate at which an object of type *i* is removed in a conflict with *j*), and the coefficients $T_{ij}$denote the transmission from a neighboring cell *j* to cell *i* [10]

Collisions are specified in ACE to require at least two colliding bodies. Taking a simple two-body collision as an example, an emitter with mass Mp and a target with mass Mt collide with a specific impact velocity Vimp. There is one most important quantity in the whole collision evolution: the specific energy of the catastrophic fragmentation threshold, Qij, which is defined as the normalized energy when the mass of the largest fragments has half of the original target mass [11].

$$\begin{aligned} Q_{ij}^* \quad &= [5 \times 10^2\, J/kg (\frac{s_{ij}}{1\, m})^{-0.37} \\ &+ 5 \times 10^2\, J/kg (\frac{s_{ij}}{1\, km})^{1.38}] (\frac{v_{imp}}{3\, km/s})^{0.5} \\ &+ \frac{3G(m_i + m_j)}{5 s_{ij}}, \end{aligned}$$

The two items in curly brackets: 1 is the strength to be destroyed by the collision, and 2 is the gravitational potential to be destroyed by the collision. The smaller brackets are the scaling by the impact velocity $v_{imp}$.

## 3. Simulation of Protoplanetary Disks

RADMC-3D is a software package for astrophysical radiative transfer calculations in arbitrary 1D, 2D and 3D geometries. It is written to solve the radiative transfer of a multi-dust medium continuum, whose radiative transfer of dust is based on Monte Carlo methods, and can be applied to a class of objects such as protoplanetary disks, pre-stars, protostars, molecular cloud cores, etc. RADMC-3D can be used to make a model of its own, and also to calculate model results using its post-processing functions, such as making spectra and images of the model.

### 3.1 Simulation Results of Radmc-3D

The protoplanetary disk was simulated and analyzed using the built-in parameters in RADMC-3D, which in turn gave a basic understanding of the disk model.HL Tauri, a well-known early star with a periastronic disk, has been reviewed in the literature to collect its physical parameters from multiband observations, which were applied to RADMC-3D to simulate it, and simulations and observations were compared and analyzed ( Figure 1-4). According to the default parameters, the following results can be simulated.

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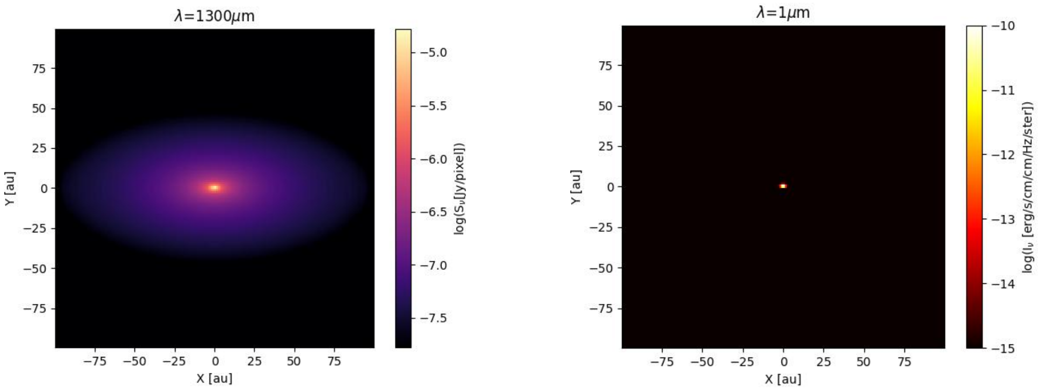


Fig. 1. Imaging plots at 1.3 mm (left) and at 1 um (right) wavelengths, with the color representation of the different radiances in the right vertical coordinate.

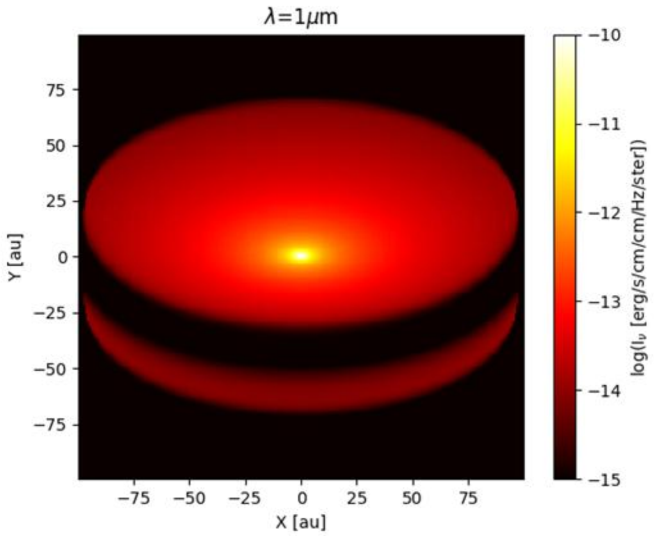


Fig. 2 Scattered light imaging at 1um wavelength, Scattered light imaging is plotted on the basis of Fig. 1. taking into account the mutual scattering of dust photon energies within the disk.

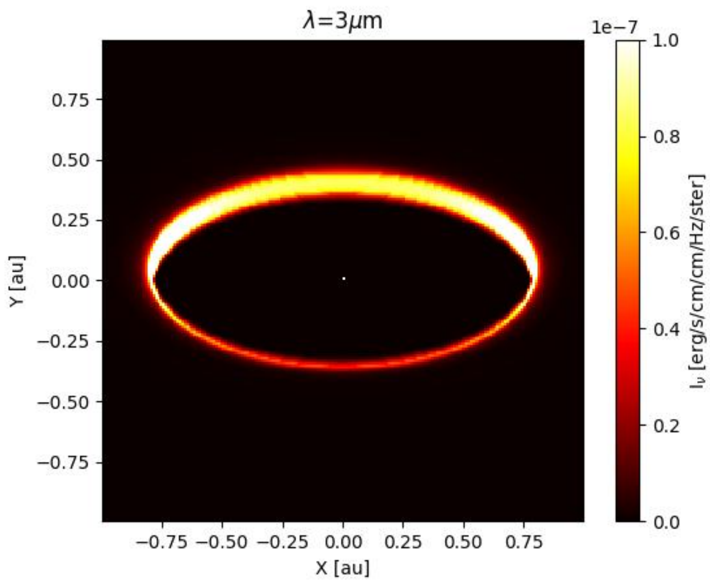


Fig. 3. Imaging of inner radius scattered light at 3um wavelength.

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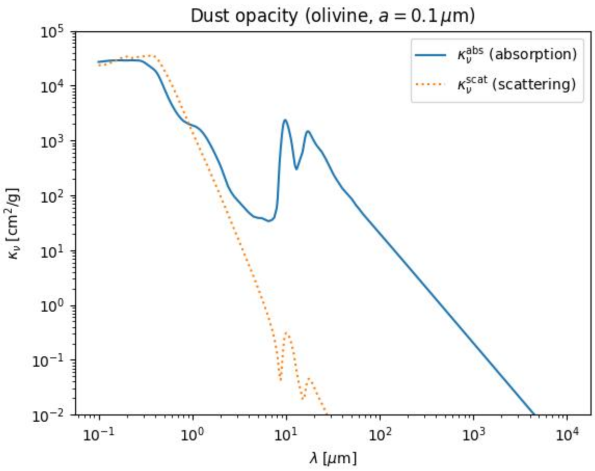


Figure 4. Optical depth map

Figure 4 shows the optical depth distribution of the disk under filling with 0.1 um size dust particles. Optical depth is a measure that describes the degree of attenuation of light waves due to absorption and scattering as they pass through a medium. The solid blue line indicates the absorption line and the dashed orange line indicates the scattering line. The absorption line appears to be concave at 10um, and this part of the concavity may be related to the size of the dust particles. The optical depth increases significantly when the size of the dust particles is close to the wavelength. The size of the dust particles in this figure happens to have an effect on the radiation in the 10 to 40 micron band. Because blue light waves are more easily scattered by small particles than red light waves, the optical depth of small particles will be higher in the blue light band, so the optical depth in the left region of the figure presents a higher value.

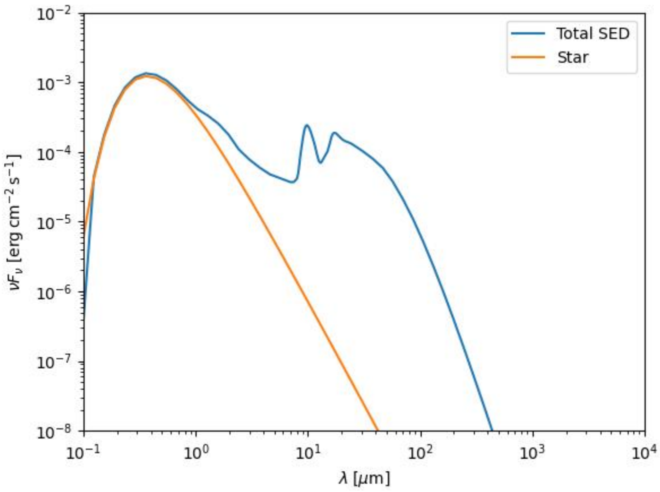


Fig. 5 Spectral energy distribution (SED) plot

Figure 5 shows the spectral energy distribution of the disk, with the horizontal coordinates indicating the wavelength and the vertical coordinates indicating the intensity of the radiation; the orange line indicates the intensity of the emission from the central star, and the blue line indicates the intensity of the emission from the entire disk system; the blue line is exceeded in the infrared wavelengths compared to the orange line, due to the periastronic disk's absorption and re-radiation of the light from the primary star.

### 3.2 Simulation and Analysis of the Early Disk-Bearing Star Hl Tauri

HL Tauri is a famous young star+disk system located in the TMC (Cloud Complex). The protoplanetary disk was photographed and resolved in detail for the first time in 2014 using the

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submillimeter/mm telescope ALMA [3]. At a distance of ~140 pc from Earth and an age of ~1 Myr, ALMA's high-resolution imaging observed the substructure of the protoplanetary disk, which is crucial for understanding the formation of planetary systems and provides valuable clues for the study of planet formation and disk evolution. The parameters used for the simulation are listed in Table 2 below. Default values were chosen for more parameters.

Table 1 Table of simulation parameters for HL Tau

| | | |
|---|---|---|
| incl_cont_stellarsrc | False | Continuous stellar source switch (true or false) |
| incl_disc_stellarsrc | True | Discrete stellar source switch (true or false) |
| mstar | [5e-6*ms] | Mass of the star |
| pstar | [0.0, 0.0, 0.0] | Position of the star |
| rstar | [2.0*rs] | Radius of the star |
| staremis_type | "blackbody" | Emission type of the star |
| tstar | [4000, 0] | Effective temperature of the star |

The simulation results are shown below.

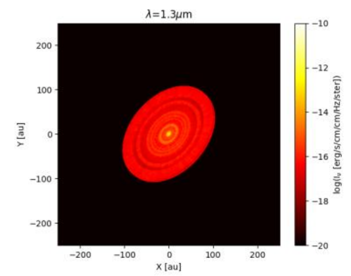
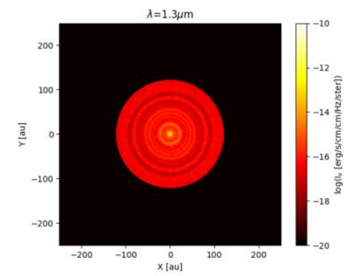
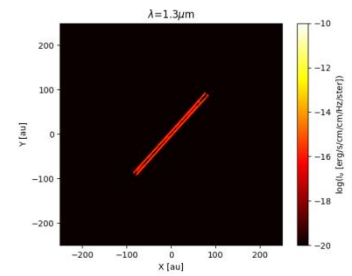
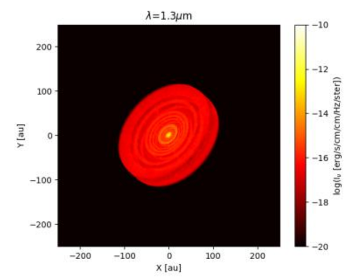
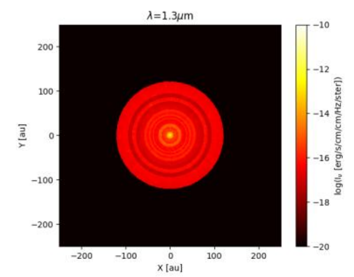
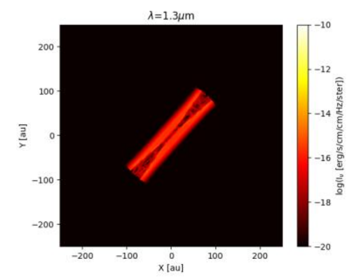
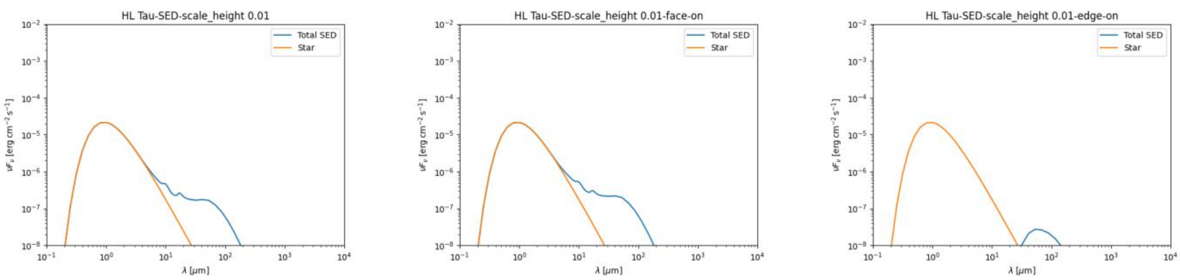
| Angle of inclination 47° | Angle of inclination 0° | Angle of inclination 90° |
|---|---|---|
|  hrdisk=0.01 |  hrdisk=0.01 |  hrdisk=0.01 |
|  hrdisk=0.05 |  hrdisk=0.05 |  hrdisk=0.05 |

Fig. 6. disk imaged at different inclination angles at 1.3mm



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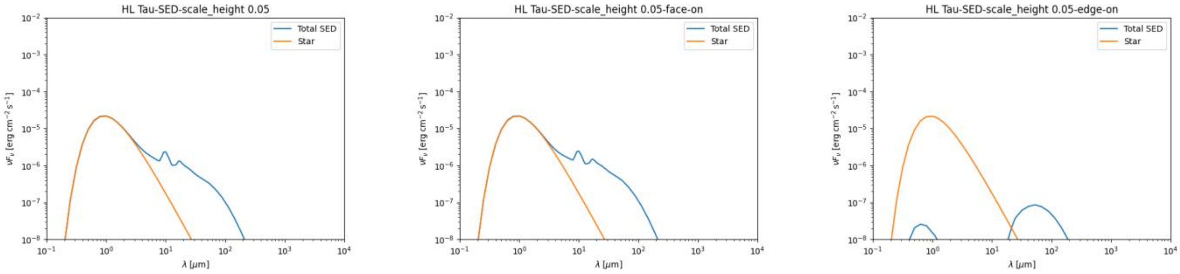

Fig. 7 SED maps corresponding to each of the imaging maps in Fig. 6

For the imaging map analysis (Fig. 6), hrdisk, also known as scale height, indicates the degree of disk abduction. Observation of the imaging map reveals that the simulated disk image fits the observed image best when hrdisk is taken as 0.01. The larger the scale height, the higher the disk's abduction degree when there is a tilt angle, and the blurrier the seams. As long as the tilt angle of the image is not zero, the elevation can be inferred because the degree of abduction cannot be observed when the disk is facing the front.

For the SED plot (Figure 7) the higher the value of hrdisk is analyzed, the higher the radiation intensity of the disk is, which increases the radiation intensity of the whole system, so the elevation can also be inferred by comparing the SED plot. The radiation intensity of the disk toward the front will be slightly higher than the radiation intensity of the inclination angle of 47 °, the size of the observed radiation intensity may be affected by the radiation emission angle. For the SED map with an inclination of 90°, the exact radiative flux cannot be measured due to the obscuration of the star and the inner and outer dust disks

## 4. Conclusion

This paper describes the evolution of protoplanetary disks and the theoretical methods used to physically model them and simulate actual objects. In the simulation part, the paper explores the effect of different physical parameters on the disk model using the RADMC-3D program, and simulates HL Tauri at 1.3 mm wavelength, analyzing its optical and dust structure at different inclinations and elevations, and obtaining best-fit results.

To summarize the results of the simulation study in this paper:

The parameters that significantly affect the radiative flux of the disk without considering scattering are Mstar, rstar, rin, rout. The parameters that significantly affect the radiative flux of the central star are Mstar, rstar, tstar.

The higher the value of hrdisk, the higher the degree of disk outward advection at non-zero inclination, and the more the slit is The higher the value of hrdisk, the higher the abduction of the disk at non-zero inclination and the more fuzzy the gap is. Meanwhile, the higher the value of hrdisk, the higher the radiation flux of the whole disk, and the scale height can be inferred by comparing with the SED diagram.

At short wavelengths, detecting the presence of hot dust and its sources is a key problem to be solved in the next decade. At long wavelengths, ALMA will provide a resolved image of the cold disk region while detecting the warm inner part of the region in the same source to determine the position of the central star [12,13]. The disk fades at longer wavelengths, some of which may be difficult to detect. So the detection of cold disks requires observational equipment sensitive to the long wavelengths, and currently the resolving equipment that can obtain resolution at this wavelength are ALMA, COBE, SWAS, etc., as well as the upcoming ngVLA, SKA.

There are several key questions that may become the focus of research in the next decade. The most challenging of these is: what is the primary mechanism for stirring the debris disk: planets, embedded massive stars or both? What is the range of stirring levels in the disk? The challenge for theoretical modeling will be to balance detailed studies of the dynamics and collisional evolution of specific systems with the need to interpret observations of a wide range of disk systematics so that

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meaningful constraints on the underlying physics can be extracted. As disks are described in increasing detail, but we have yet to account for the different properties of their halos, explanations of the breadth range of disks and the relationships between the multiple components (and the impact of these components on our interpretation of the statistics) remain to be discovered. [13]

There are several very important questions for both modeling and observational studies; do planets actually exist in inner cavities or gaps in debris disks? Direct imaging of planets is unlikely to be applicable to all systems, but higher resolution disk images can solidify the link between disk structure and planetary populations. The eccentricity of the disk places effective constraints on the masses and orbits of the planets when the inner disk edges can be resolved [13]. The current study of disk modeling has some limitations and still needs to be further refined with the next generation of telescope observations.

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