# Current Understanding of Young Circumstellar Disks: Observations of Gaseous Protoplanetary Disks

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## ABSTRACT

I provide a very brief overview on recent observations of protoplanetary disks, focusing on statistical studies about disk lifetime and mass, high-angular-resolution imaging in scattered light at near-infrared wavelengths and in thermal emission from dust grains in submillimeter. Although the angular resolution of *SPICA* is not sufficient to resolve detailed structure, *SPICA* will contribute to investigations of gas content in disks which is a fundamental property to understand planet formation and evolution. In addition, detection of water and organic molecules will be important in the astrobiological context. Combining observations at other wavelengths will allow us to appropriately interpret the observed data and extract the realistic properties of protoplanetary disks.

## 1. OBSERVATIONS OF PROTOPLANETARY DISKS

It is ubiquitously known that young stars are surrounded by rotating disks consisting of gas and dust particles, resulting primarily from conservation of angular momentum of the parent molecular clouds. Since those disks are believed to be the sites where planets are born, they are called as protoplanetary disks. The longstanding, even growing interest in understanding planet formation process has stimulated enormous observational efforts of protoplanetary disks, but we are still far from establishing their properties. We know few direct evidence of on-going planet formation, and it is even difficult to say whether each disk is capable of yielding planetary bodies. There is no doubt that disks will remain quite important targets for *SPICA*.

Most observations have been done for disks after the ages of 1 Myr partly because it is easier to detect them without contamination from the surrounding remnant of the molecular cores. The majority of disks at this phase are initially optically thick and gas-rich, meaning that they can still be in the era of formation of gas giant planets. As a *typically-observed* property, the disk mass is roughly about 1% of the stellar mass and its size is ∼100 AU, corresponding to 1″ in the nearest star-forming regions (Williams & Cieza 2011, for a review). In protoplanetary disks at ∼1–10 Myr, planet formation will occur or is ongoing. It is also possible that formation has recently completed. Thus, what we can learn from them is the initial condition of planet formation, or such as disk-planet interaction, evolution of planetary orbits, and possibility of building another planet that may be triggered by the one which has already formed. In either case, the observational data most likely reflect the combined effect of evolution and intrinsic diversity of disks. As a phenomenon, this can be described by transformation of the interstellar gas and dust, and transport of material in radial and vertical directions within a disk, which is determined by, and can affect the density and temperature structure.

Therefore, the underlying purpose of every observation is simple to say; to measure the actual physical and chemical structure. In practice, however, it is still very challenging. For instance, the density distribution is one of the very basic properties, but it has just started to emerge thanks to the recent submillimeter/millimeter interferometers providing sub-arcsecond angular resolution. In addition, to obtain a comprehensive picture with distinguishing evolution and intrinsic diversity, and to compare the disk properties with the detections of mature exoplanets, the disk property should be investigated at various evolutionary stages, for a wide-range of stellar masses, and under various star-forming environments to consider the influence such as from stellar multiplicity, strength of external radiation field, and metallicity (Harris et al. 2012; Mann & Williams 2010; Yasui et al. 2009).

Disks can be observed in thermal emission from dust grains. At least in the early evolutionary phase, a dust disk is vertically flared coupled with gaseous component where the structure is basically determined by the balance between stellar gravity and thermal pressure. In the upper layer of the disk, the surface is heated mostly by the stellar radiation, and near the mid-plane, grains are warmed up by infrared radiation from the upper surface. Warmer grains near the central star emit at shorter wavelengths, but only from the disk surface if optically thick. On the other hand, cooler grains in the outer region and even near the mid-plane can be detected in submillimeter/millimeter since a disk usually becomes optically thin at radio wavelengths. It is also possible to observe dust grains in scattered light at the wavelengths where the scattering efficiency is high. The outer, cooler region of the disk is thus accessible in optical and near-infrared using scattered light. In the case of an optically thick disk, the scattered light only traces the disk upper layer whereas the radio thermal emission comes from the mid-plane. Observing gaseous component is usually more difficult than detecting dust, but is certainly indispensable since it provides critical information such as on gas kinematics, temperature, and chemical evolution. Various atomic and molecular emission lines are expected from the location at an appropriate density and temperature for individual line transitions like [C II], [O I], water, as well as abundant CO.

## 2. DISK LIFETIME AND MASS

Lifetime of a disk provides a strong constraint on the timescale of planet formation. A method commonly-used for estimating the lifetime is to measure the disk frequency in a cluster at a certain age (Hernández et al. 2007; Hillenbrand 2005; Mamajek et al.; Haisch et al. 2001). The age is one of the most difficult quantities to accurately determine (e.g., Bell et al. 2013), but the cluster age is statistically obtained and expected to have less uncertainty than that for each star, except for the potential systematic errors such as in the distance and extinction for the cluster, and in the model isochrones. As an indicator of a disk, infrared excess has widely been used for the dust component whereas gas accretion is often identified with H$\alpha$ or Br$\gamma$ (Fedele et al. 2010). The past observations show the decay of disk frequency with the cluster age, which can be expressed by an ad-hoc, exponential decrease with the characteristic timescale of disk dispersal of 2–3 Myr. Until 10 Myr, most stars lose their disks although the frequency is not exactly zero. Therefore, statistically speaking, giant planet formation should finish until then.

If giant planets form in 1–10 Myr, there should remain enough amount of material within a disk. The disk mass has been estimated from dust continuum emission at submillimeter and millimeter wavelengths because the emission is mostly optically thin and suitable for looking into the disk mid-plane where the bulk of mass resides (Lee et al. 2011; Andrews & Williams 2007, 2005; Beckwith et al. 1990). The previous observations show that significant fraction of disks are heavier than that required to produce planetary systems like our Solar System, ~0.01 $M_\odot$. The dependence on stellar mass has also been investigated and the recent work found the linear relation between disk mass and the stellar mass in the Taurus region, for stars with spectral types earlier than M8.5 (Andrews et al. 2013). At the same time, however, there is a considerable scatter in disk mass (~0.7 dex; Andrews et al. 2013), which can be attributed to the uncertainty in the conventional prescription of obtaining disk mass. To convert the observed flux density to the mass of dust grains, we need to assume the opacity and temperature. Direct measurement of the opacity is hardly possible and extensive observations with multiple lines are required for determination of the temperature. The gain opacity is expected to change with grain size (relative to the observing wavelength) (Draine 2006), and dust temperature can also change by the evolutionary effect like grain growth and dust settling toward disk mid-plane. In addition, the dust mass is converted to the total mass usually assuming the gas-to-dust mass ratio of 100, which is the value in the interstellar medium and it is not sure at all whether the ratio is preserved in disks at 1–10 Myr. Therefore, it is expected that the evolution of disk material can affect these assumptions significantly. Note also that the mass inferred in this way is for dust grains which are efficient emitters in these wavelengths, and does not show the mass of planetesimals and planets which may have already formed.

## 3. A FEW NOTABLE EXAMPLES OF SPACE INFRARED OBSERVATIONS

As recently reported, hydrogen deuteride (HD) can be a promising probe to the gas mass. Since the majority of gas is in molecular hydrogen which has no dipole moment, observations often rely on the abundant CO to estimate the gas mass, but always encounter the significant uncertainty in freeze-out effect, temperature, and molecular abundance. HD has a weak dipole moment which yields much stronger line intensity than molecular hydrogen, and less affected by various uncertainties compare to CO. The *Herschel* data showed the detection of HD at 112 $\mu$m with 9 sigma for the disk of TW Hya, providing the estimate of disk mass larger than 0.05 $M_\odot$ (Bergin et al. 2013). TW Hya is about 10 Myr old, and it is surprising that such an old star is still gas-rich. It should also be noted that detecting molecular hydrogen is the sensitivity issue and mid-infrared $H_2$ emission lines can be good target for *SPICA*.

*Herschel* has also been successful to detect emission lines of water vapor (Hogerheijde et al. 2011). Water is one of the most abundant molecules in gas phase and icy mantles of dust grains, and found in comets, asteroids, and planets. Although hot water vapor near the central star has been found, the detection of cold water beyond snow line was first brought by *Herschel*/HIFI for the disk of TW Hya. The emission line is considered to arise from the upper layer of the disk, which suggests the underlying icy solids near the mid-plane. Their modeling work suggests the presence of ice reservoir of at least several thousands of Earth oceans.

## 4. RECENT HIGH-ANGULAR-RESOLUTION OBSERVATIONS

Detailed structure of protoplanetary disks provides indications of physical process which regulates disk evolution, and possible existence of young planets. Therefore, higher-angular-resolution, as well as higher sensitivity, certainly advances understanding of planet formation. There is one class of objects to which great attention has been paid because they invoke the presence of planets (Strom et al. 1989; Calvet et al. 2002). On the basis of spectral energy distributions associated with the deficits of mid-infrared excess, they are predicted to have dust holes or radial gaps separating inner and outer disks. In fact, the inner cavities were resolved in the dust continuum observations with SMA with the resolution of ~$0''.3$ for some of those disks (Andrews et al. 2011). The radii of the resolved cavities are 15–70 AU, and the mechanism to produce such a large cavity is under extensive discussion. One of the possible explanations is the disk clearing by one or multiple planets (Zhu et al. 2012; Dodson-Robinson & Salyk 2011).

A slightly different picture has been obtained for the same class of disks by recent scattered light imaging in near-infrared. At this wavelength regime, the angular resolution of less than $0''.1$ ($\simeq$10 AU) can be achieved by the combination of large aperture (8–10 m) telescopes and adaptive optics from the ground. It has also been demonstrated that polarization differential imaging (PDI) technique is fairly useful to observe the inner region ($\gtrsim 0''.15 \simeq$20 AU in radius) by suppressing the unpolarized, bright halo of a central star. What is emerging from PDI with adaptive optics is a morphological diversity,

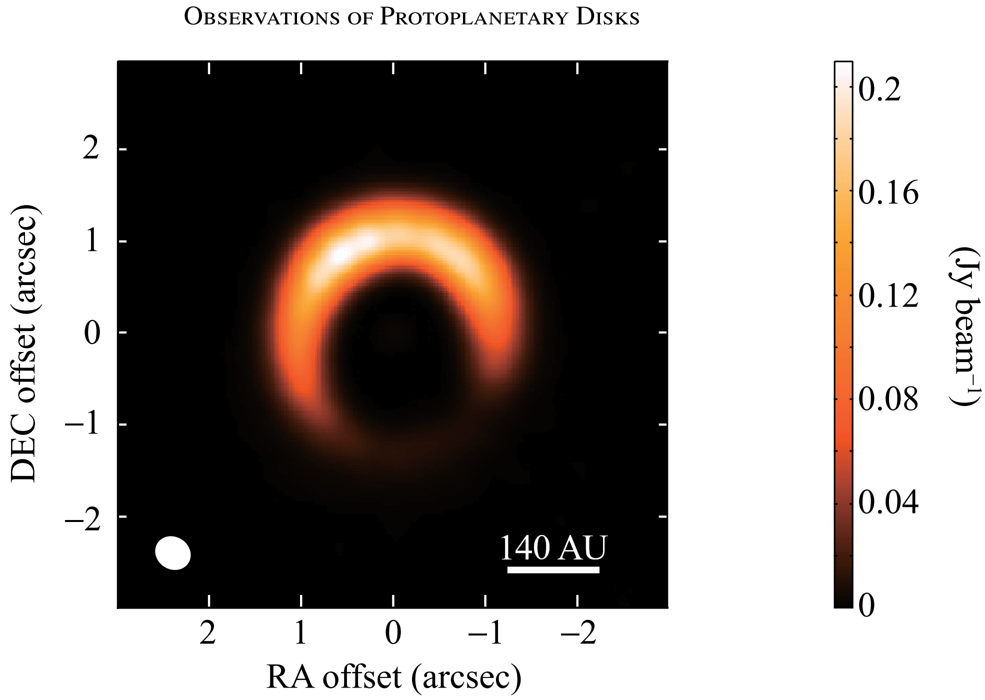


**Figure 1.** Dust continuum at 336 GHz (890 $\mu$m) for the disk of HD 142527 observed with ALMA (Fukagawa et al. 2013). The synthesized beam size is $0\farcs39 \times 0\farcs34$ (= 55 AU × 48 AU) with the major-axis PA of 57°. The horse-shoe shaped, outer disk shows the strong azimuthal asymmetry between the northern and southwestern regions.

such as gaps, spirals, and sometimes very complex, non-axisymmetric structures (Hashimoto et al. 2011; Mayama et al. 2012; Muto et al. 2012; Grady et al. 2013; Quanz et al. 2013). Comparing the distribution of scattered light with that of submillimeter dust emission, there are notable differences between them. For instance, some show cavities both in submillimeter thermal emission and scattered light while others exhibit submillimeter cavities filled with scattered light (Dong et al. 2012). The difference can be attributed to the different density distribution depending on the grain size (Dong et al. 2012), but in some cases, it may be due to the lower angular resolution in submillimeter.

We need to wait a little more to obtain the comparable ($<0\farcs1$) resolution with ALMA, but the exciting results have already started to come. As a few examples, ALMA observations toward two disks with known radial gaps revealed the strong asymmetries in the outer disks in azimuthal direction (van der Marel et al. 2013; Casassus et al. 2013; Fukagawa et al. 2013). The azimuthal contrast in flux density reaches to at least 130 at 690 GHz for the disk of Oph IRS 48 (van der Marel et al. 2013), and ~30 at 340 GHz for another case, HD 142527 (Casassus et al. 2013; Fukagawa et al. 2013) (Figure 1). These imply the localized, mass concentration which might accelerate grain growth and subsequent planetesimal growth. We have been attracted by the possible planets within the gap, but the data suggest that the outer, ring-like disk itself can be the forming site of rocky objects or gas giant planets.

Combining with infrared imaging that can mainly probe the (sub)micron-sized grains, it is implied that larger grains are localized in the submillimeter-brighter region for Oph IRS 48. Segregation of dust particle size has been investigated in radial direction (Pérez et al. 2012), but now the azimuthal size segregation is also recognized as an important sign of planet-forming activity. In addition, for some of the brightest disks, we already have the set of spatially-resolved images at multiple wavelengths from optical/near-infrared to radio, which allows us to put constrains on the density and temperature distributions through radiative transfer modeling. The fact is that the real disk structure is very complex as uncovered by recent observations, and an appropriate interpretation (modeling) of the observed data is more and more important these days.

## 5. ADVANTAGE OF *SPICA*

The angular resolution that will be obtained with *SPICA* is not enough to resolve detailed structure of protoplanetary disks (~1″ in radius). However, this does not mean that *SPICA* cannot contribute to this science case at all. The significant merit of using *SPICA* can be found in its capability of longer IR spectroscopy with the unprecedented sensitivity. For instance, $H_2$ and HD observations can give us information on gas mass which is fundamental to understand planet formation and evolution. Detection of water and organic molecules, which is difficult from the ground, will be quite important in the astrobiological context. In addition, *SPICA* and other high-angular-resolution observations are complementary to each other. To interpret the data from gas observations, radiative transfer modeling is normally required with the assumption of temperature and density distributions. For example, the disk mass estimate with HD was obtained through such modeling attempts, and the uncertainty remains in temperature structure (Bergin et al. 2013). Additional observations of multiple gas temperature tracers are valuable and ALMA can provide those.

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