IAU 8th Asia-Pacific Regional Meeting
ASP Conference Series, Vol. 289, 2003
S. Ikeuchi, J. Hearnshaw & T. Hanawa, eds.

Investigation of the Physical Properties of Protoplanetary Disks around T Tauri Stars by a High-resolution Imaging Survey at $\lambda = 2$ mm

Munetake Momose

Institute of Astrophysics and Planetary Sciences, Ibaraki University, Bunkyo 2-1-1, Mito, Ibaraki 310-8512, Japan

Yoshimi Kitamura

Institute of Space and Astronautical Science, Yoshinodai, Sagamihara, Kanagawa 229-8510, Japan

Sozo Yokogawa

Graduate University for Advanced Studies, National Astronomical Observatory of Japan, Osawa, Mitaka, Tokyo 181-8588, Japan

Ryohei Kawabe, Motohide Tamura

National Astronomical Observatory of Japan, Osawa, Mitaka, Tokyo 181-8588, Japan

Shigeru Ida

Tokyo Institute of Technology, Ookayama, Meguro-ku, Tokyo 152-8551, Japan

Abstract. Dust continuum emission at 2 millimeters from the disks around 13 T Tauri stars was imaged with the spatial resolution of $1'' - 2''$. Disk properties are derived from the combination of image-based model fitting and the analysis of the spectral energy distributions. We found a tendency for disk expansion with decreasing accretion activity, which can be interpreted in terms of the evolution of an accretion disk. The derived surface density distribution of the disks may suggest that it is difficult to make planets like the solar system without the redistribution of solids.

1. Introduction

Low-mass pre-main-sequence stars (T Tauri stars) are commonly accompanied by circumstellar disks. Their physical properties have been derived mainly from analysis of spectral energy distributions (SEDs), revealing that the disks contain gas and dust of $(0.1 - 0.001)M_{\odot}$ within several hundred AU in radius (Beckwith & Sargent 1996). Since such characteristics are reminiscent of the "primordial solar nebula" (e.g., Hayashi, Nakazawa, & Nakagawa 1985), these are believed to be the precursors of planetary systems, or "protoplanetary" disks. Understand-

2003ASPC..289...85M

ing of the internal structure and evolution of the disks in the early T Tauri stage, however, is still limited. It has been revealed that the mass accretion rate from the disk to the central star gets lower as the stellar age increases in the classical T Tauri stage (Calvet, Hartmann & Strom 2000), but it is unclear how this evolutionary trend is related to the internal structure of the disks themselves. We have carried out an imaging survey of protoplanetary disks associated with single T Tauri stars in Taurus Molecular Cloud ($d = 140$ pc) in dust continuum emission at $\lambda = 2$ millimeters with the Nobeyama Millimeter Array (NMA). Physical properties of the disks, including the outer radius and the surface density distribution, have systematically been derived from the combination of SED analysis and image-based model fitting.

2. Observations

Observations were made with the NMA over three winter seasons of 1998 – 2001. In our survey disks around 13 stars were imaged: 11 are T Tauri stars while 2 (HL Tau, Haro 6-5B) are objects embedded in a tenuous envelope. Prior to the high resolution imaging, we measured the total flux density from a disk with a larger beam ($\sim 5''$ beam, or $\sim$ 700AU resolution) of the compact D configuration. We used these total flux densities to check the depth of integration for successive higher-resolution images with the AB ($\sim 1''$ beam) or AB+C ($\sim 2''$ beam) configurations. More details on the sample selection and observations are found in Kitamura et al. (2002).

3. Results and Discussion

Figure 1 shows the obtained high-resolution images. Each emission feature is more extended than the beamsize, indicating that the disk emission is spatially resolved. To estimate the physical properties of the disks, we analyze the disk images and the SEDs on the basis of two disk models; one is a power-law model frequently used in data analysis of disk observations (e.g., Beckwith et al. 1990), and the other is a similarity solution for a viscous accretion disk (Lynden-Bell & Pringle 1974). The disk parameters to be determined are as follows: inner and outer radii ($R_{\rm in}$, $R_{\rm out}$), surface density distribution ($\Sigma(r)$), inclination angle (i), position angle (PA), temperature distribution ($T(r)$), and dust opacity coefficient with the β index. Among these parameters, $R_{\rm out}$, $\Sigma(r)$, i, and PA are determined by the image-based model fitting while $R_{\rm in}$, $T(r)$, and β are by the SED-fitting. Since both the disk models give consistent results with each other, we will only show the case of the power-law disk model in the following (see Kitamura et al. 2002 for more details). Good measures of the disk evolution are necessary when we extract evolutionary trend or diversity in disk physical parameters, i.e., the clock. In this study two clocks are adopted: the age of the central star and the Hα line luminosity (L(Hα)) which is well correlated with the mass accretion rate in the disks (Cabrit et al. 1990). The most intriguing correlation is shown in Figure 2: $R_{\rm out}$ seems to increase with decreasing L(Hα). This trend can be interpreted as radial expansion of an accretion disk due to outward transport of angular momentum (Lynden-Bell & Pringle 1974). The viscosity transports angular momentum from the inner to outer parts of the disk,

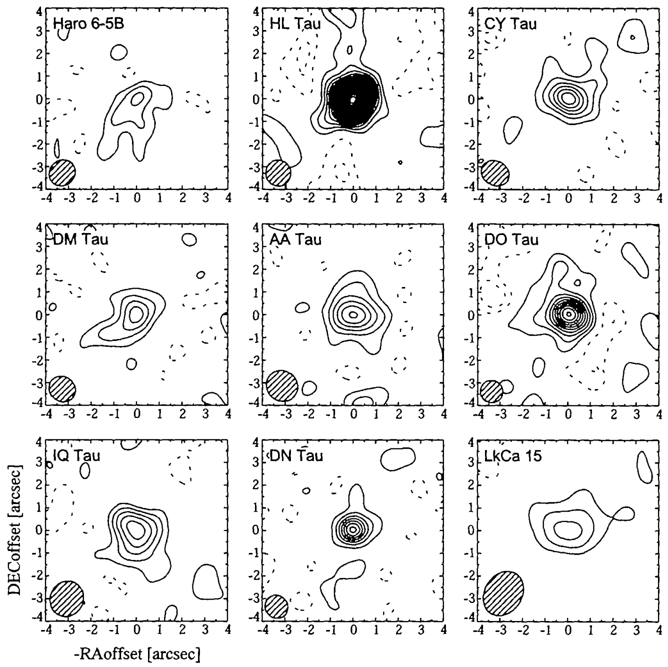

Figure 1. Images of 2 mm dust continuum emission toward 13 T Tauri stars. The contour lines start at 1.5σ and -1.5σ levels with intervals of 1.5σ. The negative levels are written by broken lines. The hatched ellipse in each panel indicates the beamsize (FWHM).

resulting in the accreting motion of the inner part and the expansion of the outer part. If we compare the disk expansion with the similarity solution for viscous accretion disks, the observed increase rate of $R_{\rm out}$ suggests $\alpha \sim 0.01$, which is predicted in theoretical models for the MHD turbulence (Balbus & Hawley 1998). The trend, however, becomes unclear against the stellar age (Figure 2). These results may suggest that the disk evolution does not synchronize well with the stellar evolution. We found no evolutionary trend in surface density distribution. The surface density at 100 AU ranges from 0.1 to 10 g cm^{-2}, which is consistent with the extrapolated value at 100 AU in the Hayashi model, suggesting the outer parts of the disks have enough matter to form small bodies like the Edgeworth-Kuiper Belt Objects. The power-law index p of $\Sigma(r)$ ($\Sigma(r) \propto r^{-p}$), on the other hand, mainly falls into a range of 0 to 1, smaller than the index of 1.5 predicted in the Hayashi model. Such flat distributions of the surface density might prohibit the formation of giant planets in the innermost regions of the disks if the low values of p hold even in the innermost parts, where planets will be formed. One possible solution to this problem is reshuffle of solids within the disks, i.e., inward movement of solids (Stepinski & Valageas 1997). Of course, our observations were insufficient to derive convincing conclusions on this issue. The large scatters of p or $\Sigma_{\rm 100AU}$ might indicate some diversity in the viscosity processes in the disks or initial conditions for planet building. The diversity found in the physical properties of the protoplanetary disks is likely to be one of the main causes that produce the diversity seen in the planetary systems including both our solar system and extra-solar systems being discovered (e.g.,

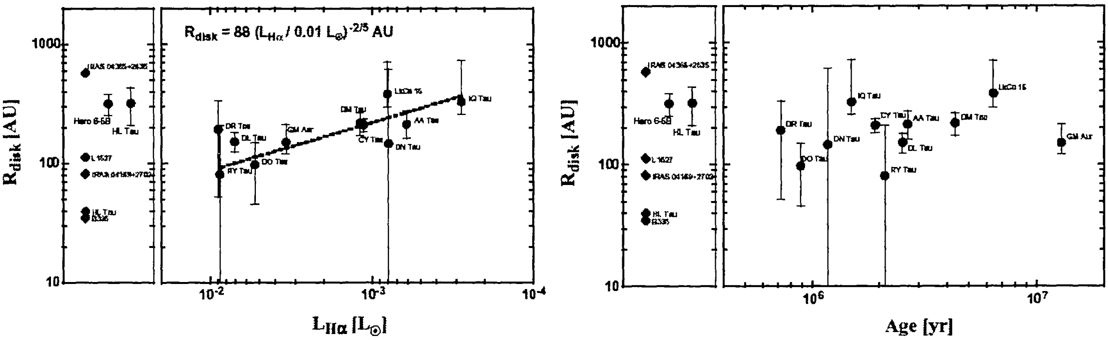

Figure 2. (left) Disk outer radius vs Hα line luminosity. The best-fit curve, shown by a broken line, is $R_{\rm out} = 88(L_{\rm H\alpha}/0.01L_\odot)^{-2/5}$ AU. The left panel shows the results for the two embedded sources without the abscissa and shows the centrifugal radii derived by Ohashi et al. (1997). (right) Disk radius vs. stellar age.

Marcy & Butler 1998). It has not been well understood as yet, however, which property of the protoplanetary disks produces the difference between the hot Jupiters and our planets. Theoretically it is of great significance to generalize the planet formation processes so as to be applicable to any planetary system. The initial conditions, i.e., the starting point of the generalized models, should be provided by imaging observations with extremely high resolutions and sensitivities. Great advances in understanding of planet formation must be achieved by a next-generation array, the Atacama Large Millimeter and submillimeter Array (ALMA) to be operated in ~ 2010 in Chile.

References

Balbus, S. A. & Hawley, J. F. 1998, Reviews of Modern Physics, 70, 1

Beckwith, S. V. W. & Sargent, A. I. 1996, Nature, 383, 139

Beckwith, S. V. W., Sargent, A. I., Chini, R. S., & Guesten, R. 1990, AJ, 99, 924

Cabrit, S., Edwards, S., Strom, S. E., & Strom, K. M. 1990, ApJ, 354, 687

Calvet, N., Hartmann, L. & Strom, S. E. 2000, in Protostars & Planets IV, ed. V. Mannings, A. P. Boss, & S. S. Russell (Tuscon: Univ. Arizona Press), 377

Hayashi, C., Nakazawa, K., & Nakagawa, Y. 1985, in Protostars & Planets II, ed. D. C. Black & M. S. Matthews (Tuscon: Univ. Arizona Press), 1100

Kitamura, Y., Momose, M., Yokogawa, S., Kawabe, R., Tamura, M., & Ida, S. 2002, ApJ, in press

Marcy, G. W. & Butler, R. P. 1998, ARA&A, 36, 57

Ohashi, N., Hayashi, M., Ho, P. T. P., Momose, M., Tamura, M., Hirano, N., & Sargent, A. I. 1997, ApJ, 488, 317

Stepinski, T. F. & Valageas, P. 1997, A&A, 319, 1007