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Interferometric Observations of the T Tauri Stars in the MBM 12 Cloud

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ABSTRACT

We have carried out a millimeter interferometric continuum survey toward 7 YSOs in the MBM 12 cloud. Thermal emissions associated with 2 YSOs were detected above the $3\text{-}\sigma$ level at 2.1 mm, and one also showed a 1.3 mm thermal emission. Another object was marginally detected at 2.1 mm. Spectral energy distributions of the YSOs are well fitted by a simple power-law disk model. Masses of the circumstellar disks are estimated to be an order of $0.05M_{\odot}$. The circumstellar disks in the MBM 12 cloud have properties in common with the disks in nearby star-forming regions, in terms of disk parameters such as a disk mass, as well as an infrared excess.

Subject headings: stars — formation; radio continuum — stars

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1. Introduction

Physical and chemical characteristics as well as evolution process of a circumstellar disk are tightly connected to formation of stars and planets. Millimeter observations, both of continuum emission and of molecular gas emission, reveal that young stellar objects (YSOs) commonly have a circumstellar disk (Beckwith et al. 1990). Duvert et al. (2000) carried out millimeter continuum and line survey for YSOs in the Taurus molecular cloud. They detected thermal emission from all classical T Tauri stars (CTTSs) in the sample, while they did not detect emission from any weak-line T Tauri stars (WTTSs) with a disk mass upper limit of $\sim 2 \times 10^{-4} M_{\odot}$. They attribute this difference to the evolution of the circumstellar disks. Emission from a circumstellar disk, such as dust continuum emission, molecular gas emission, and an infrared excess, decrease as the disk evolves.

The MBM 12 (L 1457) cloud is a high-latitude cloud with a signature of star formation. Three LkH α stars and several emission-line stars have been identified by optical surveys (e.g. Magnani, Caillault, & Armus 1990; Ogura et al. in preparation), an X-ray survey (Hearty et al. 2000a), and a near-infrared study (Luhman 2001). Some sources exhibit mid-infrared excesses, implying circumstellar disks (Jayawardhana et al. 2001). However, no radio continuum emission nor molecular gas emission have been detected so far with an upper limit of the disk mass of $0.09 M_{\odot}$ (Pound 1996; Hogerheijde et al. 2002). Hogerheijde et al. (2002) claim a deficiency of massive circumstellar disks in the cloud. If all YSOs in the cloud do not have even a small disk, the formation of circumstellar disks should have been prevented, or the disks should have already dissipated.

Until recently the MBM 12 cloud was thought to be one of the nearest star forming regions with a distance of ~ 65 pc (Hobbs, Blitz, & Magnani 1986; Hearty et al. 2000b). However, Luhman (2001) suggests its distance of ~ 275 pc. Anderson et al. (2002) claim that there are two components toward the MBM 12 cloud, with a dense part at ~ 360 pc, and a thin layer at ~ 80 pc. If the YSOs are associated with the dense cloud, the YSOs are low-mass stars with a young age (~ 2 Myr), the same generations of or successors to the YSOs in the nearby star forming regions such as the Taurus molecular cloud. The evolution process of the circumstellar disks can be discussed by comparing the YSOs in the MBM 12 cloud with those in the nearby star forming regions.

We present here the results of a millimeter interferometric continuum survey toward the YSOs in the MBM 12 cloud. Thanks to high-sensitivity of the Nobeyama Millimeter Array, we have first detected millimeter continuum emissions from the YSOs in the MBM 12 cloud.

2. Observations and Data Reduction

Radio interferometric observations were carried out in 16 days in 2001 December, 2002 January, and 2002 December with the Nobeyama Millimeter Array. The targets are bright YSOs in the MBM 12 cloud identified by the optical and X-ray wavelengths. The array consists of six 10 m antennas operating at rest frequencies of 103.8 GHz ($\lambda = 2.9$ mm), 141.0 GHz ($\lambda = 2.1$ mm), and 224.5 GHz ($\lambda = 1.3$ mm). The signals from the antennas were sent to the Ultra Wide Band Correlator (UWBC; Okumura et al. 2000), which covers 1024 MHz with a spectral resolution of 8.0 MHz. Total system temperatures ranged from 200 K to 800 K. The spatial resolution was about $4''$ with the D antenna configuration. Due to poor weather conditions, the integration time for 230 GHz observations was strictly limited. QSO B0234+285 (4C 28.07) was used as the phase calibrator. The observations were carried out on a cycle of 15 minutes on the source and 5 minutes on the calibrator. Total on-source integration times were between 100 minutes and 300 minutes. The flux of the quasar was calibrated by the observations of Uranus about every 5 days. The derived flux have a maximum uncertainty of 20%.

The data were calibrated and reduced using the UVPROC-II package developed at the Nobeyama Radio Observatory, and the AIPS package developed at NRAO. After determining the phase and amplitude gain curve, the uv-visibilitys were gridded and Fourier-transformed using natural weighting to produce dirty maps with $0''.5$ per pixel. Each dirty map was CLEANed until 1σ noise level.

3. Results

The survey results are listed in Table 1. Continuum emissions at 2.1 mm were detected toward LkH α 262 and LkH α 264 above the 3σ level, and marginally toward S18. We also detected 1.3 mm continuum emission toward LkH α 264. At the position of the other objects, no sources were detected above the rms noise level. No objects are spatially resolved. The measured fluxes and the 3σ upper limits of the objects are summarized in Table 1. The flux uncertainties for the detected objects include rms of the sky in the map and a possible 20 % error in absolute flux calibrations. Figure 1 shows a 2.1 mm continuum contour map of the LkH α 262/263 region.

Table 1. Observed Flux Densities.

Source	$F_{2.9mm}(\text{mJy})$	$F_{2.1mm}(\text{mJy})$	$F_{1.3mm}(\text{mJy})$
LkH α 262	<5.54	10.4 ± 2.7	< 81
LkH α 263	<4.82	< 5	< 70
LkH α 263C	<4.82	< 5	< 70
LkH α 264	<10.07	15.5 ± 3.8	56.2 ± 14.5
RX J0255.4+2005	...	< 12	...
E 02553+2018	...	< 8	...
S18	...	8.0 ± 4.6	<33

The spectral energy distributions of LkH α 262, LkH α 264, and S18 are presented in Figure 2. The data were taken from the 2MASS survey, the IRAS survey, and previous optical and near-infrared photometric studies, and mid-infrared photometry (Hearty et al. 2000a; Luhman 2001; Jayawardhana et al. 2001). Observed fluxes were dereddened using A_V (Luhman 2001) with the interstellar extinction law (Rieke & Lebofsky 1985). In these figures, the upper limits are also shown. The spectral energy distributions of the objects are well fitted by a combination of a stellar photosphere model (Allard, Hauschildt, & Schweitzer 2000) and a power-law disk model (Beckwith et al. 1990). We adopt a power law form as the disk temperature $T = T_1(r/1\text{AU})^{-q}$, surface density $\Sigma = \Sigma_1(r/1\text{AU})^{-p}$, and mass opacity $\kappa_\nu = \kappa_0(\nu/\nu_0)^\beta$. At frequencies at which emission from a circumstellar disk are optically thin, $F_\nu \propto \nu^{2+\beta}$. We find $\beta = 1.0$ for LkH α 264, though uncertainties in the millimeter fluxes are very large. We assume $p = 1.0$, $\kappa_0 = 0.1$ at $\nu_0 = 10^{12}$ Hz, a disk outer radius $R_D = 100$ AU, $\beta = 1.0$, and an inclination of $\theta = 45^\circ$ for all objects. Note that because none of the objects were spatially resolved, the maximum outer radius is 550 AU for $d = 275$ pc. The spectral types of the stars are taken from Luhman (2001). The fitted disk parameters are presented in Table 2. Note that the derived disk masses in Table 2 can be easily changed by disk parameters, such as p , β , and R_D . The spectral energy distributions of the fitted power-law disk models are shown in Figure 2 by the dashed lines, those of the stars by the dotted lines, and the composite spectra by the solid lines. As seen in the figures, the upper limits of the 3 mm continuum observations (Pound et al. 1996; Hogerheijde et al. 2002) are consistent with the spectral energy distributions derived from the models. Chauvin et al. (2002) have recently discovered an edge-on disk near LkH α 263 (LkH α 263 C), whose dust mass is estimated to be $2 \times 10^{-6} M_\odot$. This implies that the gas mass of the disk is below the detection limit of our survey, though this estimated mass is highly sensitive to the disk parameters.

4. Discussion

The disk masses of the objects are around $0.05 M_\odot$, comparable to the intermediate mass disks in the nearby molecular clouds (e.g. Beckwith et al. 1990; André & Montmerle 1994).

Table 2. Disk Parameters.

Source	q	T_1 (K)	M_d (M_\odot)	r_0 (AU)
LkH α 262	0.62	152	0.048	0.023
LkH α 264	0.70	220	0.085	0.080
S18	0.65	112	0.071	0.024

Hogerheijde et al. (2002) observed 7 YSOs in MBM 12 by the ^{13}CO (2–1) line. No objects show the molecular line. Assuming a standard CO abundance, they estimated upper limits of the disk mass to be $(5 \sim 10) \times 10^{-4} M_{\odot}$, which are far smaller than our results ($\sim 0.1 M_{\odot}$). Therefore, depletion of ^{13}CO occurs in the disk with two orders of magnitude. Such a depletion is predicted by chemical models (Aikawa et al. 1996) and is indeed observed commonly in T Tauri stars (e.g. Dutrey, Guilloteau & Simon 1994).

Meyer et al. (1997) show that a YSO with an accretion disk has a near-infrared excess. A near-infrared color-color diagram of the sample is presented in Figure 3. Near-infrared magnitudes are taken from Luhman (2001) or measured by us using the UH 2.2 m telescope (Ogura et al. in preparation). As spectral types of LkH α 262 and LkH α 264 are M0 and M3 respectively, they each has a near-infrared excess. Because S18 is of spectral type of M3, it seems to suffer interstellar reddening without an intrinsic near-infrared excess. Therefore two of the YSOs with radio continuum emission have near-infrared excesses. On the other hand, the YSOs without radio continuum emission have near-infrared color consistent with no intrinsic near-infrared excess. This general trend is also seen in the sample of the YSOs in Taurus (Figure 3). This can be interpreted as follows: at least two of the YSOs with radio continuum emission have an outer portion of the disk, as well as an inner portion of the disk which generates the near-infrared excess.

Jayawardhana et al. (2001) detected near- and mid-infrared excesses from the YSOs in the MBM 12 cloud. All YSOs with radio continuum emission have the mid-infrared excesses. However it is not the case vice versa. For example, E 2553+2018 which has the largest $K - L$ excess and third largest $K - N$ excess in the sample does not have radio continuum emission. Nürnberger, Chhini, & Zinnecker (1997) conducted a radio continuum survey of T Tauri stars in the Lupus associations. They find no correlation between the infrared indices ($2.2 \mu\text{m} - 12 \mu\text{m}$) and the disk masses. Also found are no correlations for the YSOs in the Taurus molecular cloud, the ρ Oph cloud (André & Montmerle 1994), and the Chamaeleon cloud (Henning et al. 1993). However, there is a trend for the MBM 12 and the Chamaeleon clouds in which the objects with large radio continuum emission have large mid-infrared excesses and the objects without large mid-infrared excesses do not have large radio continuum emission.

The YSOs in the MBM 12 cloud are known to have a high binary frequency (Chauvin et al. 2002). In the sample, LkH α 263, E02553+2018, and S18 are binaries with small separations, whereas the other objects are single stars or a wide binary. However the small number of the sample prevents us to investigate the relationship between a binary and a circumstellar disk.

The circumstellar disks in the MBM 12 cloud detected by this survey have properties

in common with the disks in nearby star-forming regions, in terms of disk parameters, such as a disk mass, as well as an infrared excess.

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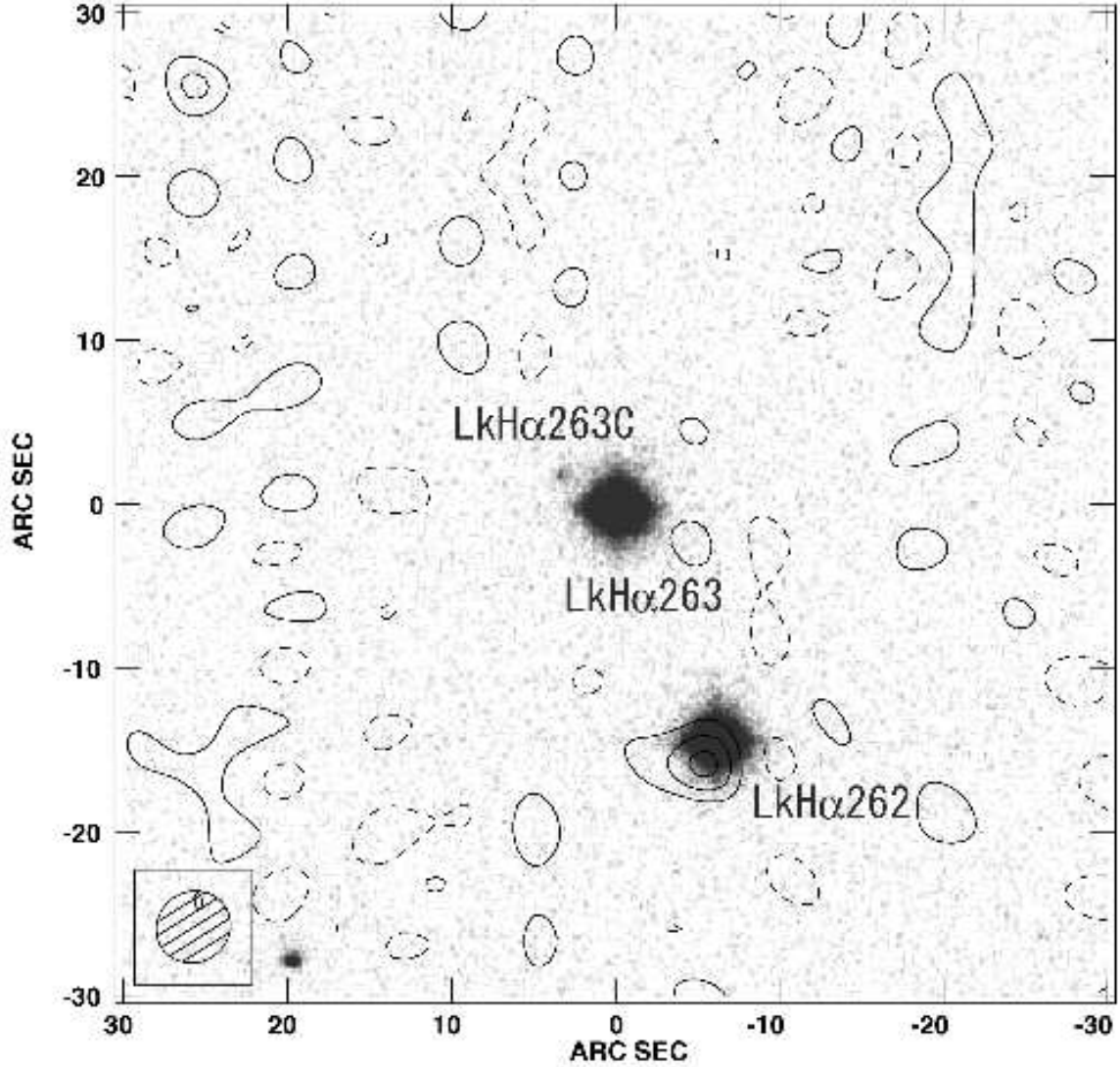


Fig. 1.— Contour of 2.1 mm radio continuum emission toward the LkH α 263 region, overlaid a near-infrared Kp -band image taken by the UH 2.2 m telescope. Contour levels are $(-1.5, +1.5, +3.0, +4.5)$ times the noise level (1.75 mJy). The synthesized beam is shown in the lower left corner of the map. Primary beam correction is not performed to this image. Radio continuum emission toward LkH α 262 is clearly detected. Coordinates are offset to the position of LkH α 263.

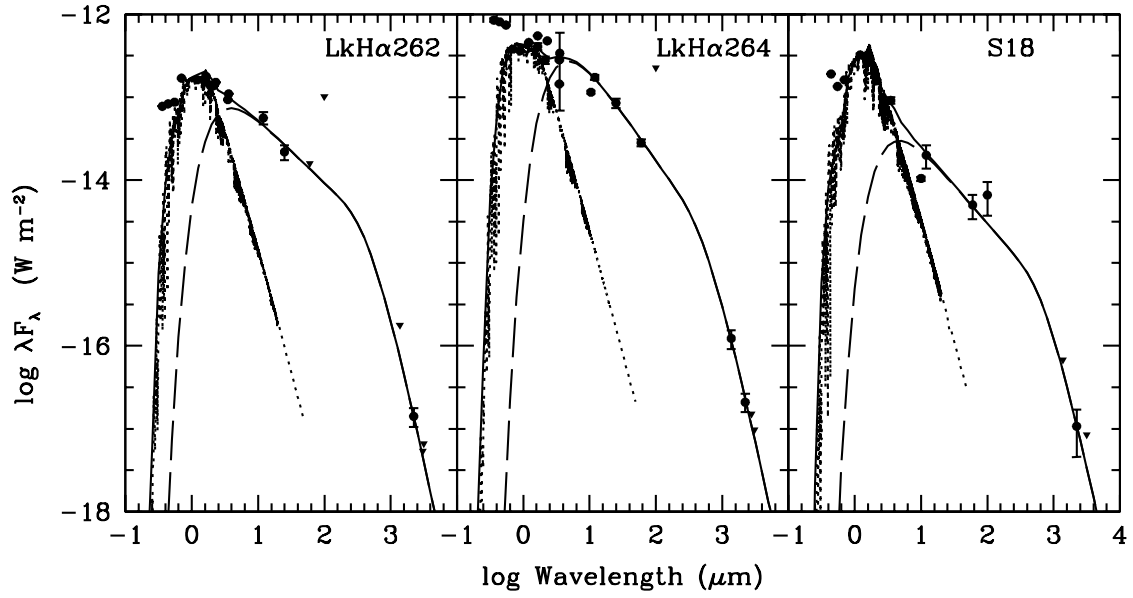


Fig. 2.— Spectral energy distributions of LkH α 262, LkH α 264, and S18. Filled circles represent the measured flux values, and filled triangles represent the upper limits of the measurements. The dotted line shows the spectral energy distribution of the central star, and the dashed line shows that of the circumstellar disk. The solid line shows the spectral energy distribution of the total flux.

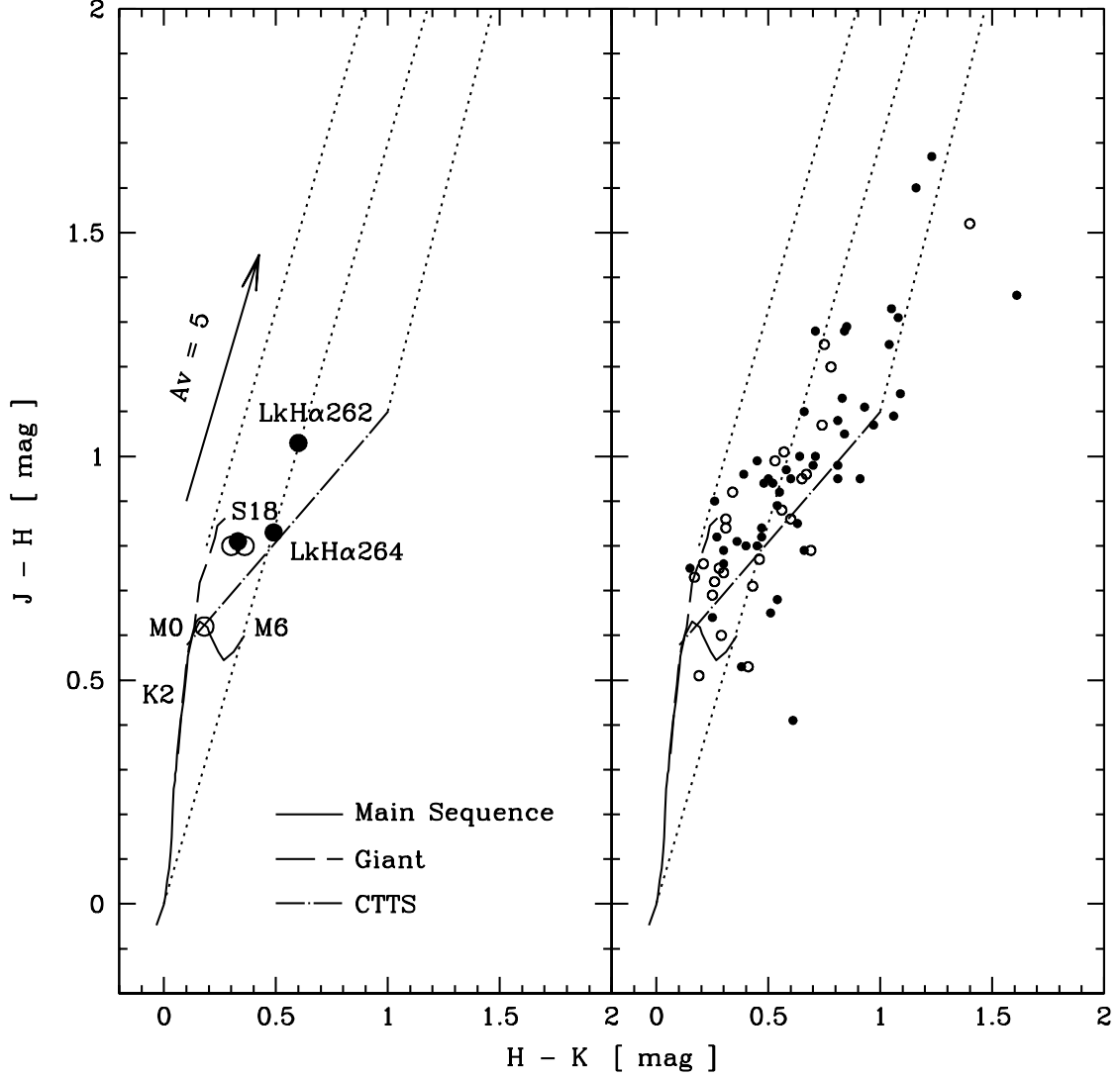


Fig. 3.— Near-infrared color-color diagrams of the YSOs in the MBM 12 cloud (left), and in the Taurus molecular cloud listed in Beckwith et al. (1990) (right). The objects with radio continuum emission are denoted by the filled circles, and the objects without emission by the open circles. The intrinsic colors of the main-sequence, giants (Bessell & Brett 1988), and classical T Tauri stars (Meyer, Calvet, & Hillenbrand 1997) are indicated. The reddening vector follows Koornneef (1983). All colors are transformed to the CIT system.