INTERFEROMETRIC OBSERVATIONS OF THE T TAUROI STARS IN THE MBM 12 CLOUD

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ABSTRACT

We have carried out a millimeter interferometric continuum survey toward seven young stellar objects (YSOs) in the MBM 12 cloud. Thermal emissions associated with two YSOs were detected above the 3 σ 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 of the order of 0.05 $M_\odot$. 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 disk mass, as well as an infrared excess.

Subject headings: radio continuum: stars — stars: formation

1.INTRODUCTION

Physical and chemical characteristics as well as the evolution process of a circumstellar disk are tightly connected to the 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 surveys for YSOs in the Taurus molecular cloud. They detected thermal emission from all classical T Tauri stars (CTTs) in the sample, while they did not detect emission from any weak-lined T Tauri stars 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 (L1457) cloud is a high-latitude cloud with a signature of star formation. Three LkHα stars and several emission-line stars have been identified by optical surveys (e.g., Magnani, Caillault, & Armus 1990; K. Ogura et al. 2003, in preparation), an X-ray survey (Hearty et al. 2000b), 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 $\sim 65$ pc (Hobbs, Blitz, & Magnani 1986; Hearty et al. 2000a). However, Luhman (2001) suggests its distance to be $\sim 275$ pc. Anderson et al. (2002) claim that there are two components toward the MBM 12 cloud, with a dense part at $\sim 360$ pc and a thin layer at $\sim 80$ pc. If the YSOs are associated with the dense cloud, the YSOs are low-mass stars with a young age ($\sim 2$ Myr), the same generation 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 the high sensitivity of the Nobeyama Millimeter Array, we have first detected millimeter continuum emission 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 (Okumura et al. 2000), which covers 1024 MHz with a spectral resolution of 8.0 MHz. Total system temperatures ranged from 200 to 800 K. The spatial resolution was about 4″ with the D antenna configuration. Owing 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 integra-

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Table 1

| Source                  | $F_{2.9\,\mathrm{mm}}$ (mJy) | $F_{2.1\,\mathrm{mm}}$ (mJy) | $F_{1.3\,\mathrm{mm}}$ (mJy) |
|-------------------------|-------------------------------|-------------------------------|-------------------------------|
| LkHα 262               | <5.54                         | 10.4 ± 2.7                    | <81                           |
| LkHα 263               | <4.82                         | <5                            | <70                           |
| LkHα 263C              | <4.82                         | <5                            | <70                           |
| LkHα 264               | <10.07                        | 15.5 ± 3.8                    | 56.2 ± 14.5                   |
| RX J0255.4+2005        | ...                           | <12                           | ...                           |
| E02553+2018            | ...                           | <8                            | ...                           |
| S18                    | ...                           | 8.0 ± 4.6                     | <33                           |

3. RESULTS

The survey results are listed in Table 1. Continuum emissions at 2.1 mm were detected toward LkHα 262 and LkHα 264 above the 3 σ level and marginally toward S18. We also detected 1.3 mm continuum emission toward LkHα 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 3 σ upper limits of the objects are summarized in Table 1. The flux uncertainties for the detected objects include the 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 LkHα 262/263 region.

The spectral energy distributions of LkHα 262, LkHα 264, and S18 are presented in Figure 2. The data were taken from the Two Micron All Sky Survey, the IRAS survey, and previous optical and near-infrared photometric studies, and mid-infrared photometry (Hearty et al. 2000b; 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.
TABLE 2

| Source   | \(T_0\) (K) | \(M_d\) (\(M_\odot\)) | \(r_0\) (AU) |
|----------|-------------|------------------------|--------------|
| LkH\alpha 262 | 0.62        | 0.048                 | 0.023        |
| LkH\alpha 264 | 0.70        | 0.085                 | 0.080        |
| S18       | 0.65        | 0.071                 | 0.024        |

\(T \approx T_0(r/1 \, \text{AU})^{-\nu}\), surface density \(\Sigma = \Sigma_0(r/1 \, \text{AU})^{-\nu}\), and mass opacity \(\kappa_v = \kappa_0(r/1 \, \text{AU})^{\nu}\). At frequencies at which emission from a circumstellar disk are optically thin, \(F_v \propto v^{2.5-\beta}\). We find \(\beta = 1.0\) for LkH\alpha 264, although uncertainties in the millimeter fluxes are very large. We assume \(\rho = 1.0\), \(\kappa_0 = 0.1\) at \(r_0 = 10^{13}\) Hz, a disk outer radius \(R_0 = 100\) 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 \(\rho\), \(\beta\), and \(R_0\). 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\alpha 263 (LkH\alpha 263C), whose dust mass is estimated to be \(2 \times 10^{-4}\) \(M_\odot\). This implies that the gas mass of the disk is below the detection limit of our survey, although 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).

Hogerheijde et al. (2002) observed seven 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 \((5–10) \times 10^{-4}\) \(M_\odot\), which are far smaller than our results \((-0.1\) \(M_\odot\)). Therefore, depletion of \(^{13}\)CO occurs in the disk with 2 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, Calvet, & Hillenbrand (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 University of Hawaii (UH) 2.2 m telescope (K. Ogura et al. 2003, in preparation). As spectral types of LkH\alpha 262 and LkH\alpha 264 are M0 and M3, respectively, they each have 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 (Fig. 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 that 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, E2553+2018, which has the largest \(K-L\) excess and third largest \(K-N\) excess in the sample, does not have radio continuum emission. Nünberger, Chini, & Zinnecker (1997) conducted a radio continuum survey of T Tauri stars in the Lupus associations. They find no correlation between the infrared indices (2.2–12 \(\mu\)m) and the disk masses. Also found are no correlations for the YSOs in the Taurus molecular cloud, the \(\rho\) 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\alpha 263, E2553+2018, and S18 are binaries with small separations, whereas the other objects are single stars or a wide binary. However, the small number in the sample prevents us from investigating 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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