Aperture Synthesis CS and 98 GHz Continuum Observations of Protostellar *IRAS* Sources in Taurus

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ABSTRACT The CS ($J = 2-1$) line and 98 GHz continuum emission have been observed for 11 protostellar *IRAS* sources in the Taurus molecular cloud with resolutions of 2.6″–8.8″ (360 AU–1200 AU) using the Nobeyama Millimeter Array (NMA). The CS emission is detected only toward embedded sources, while the continuum emission from dust grains is detected only toward visible T Tauri stars except for one embedded source, L1551-IRS5. This suggests that the dust grains around the embedded sources do not centrally concentrate enough to be detected with our sensitivity (~4 mJy r.m.s), while dust grains in disks around the T Tauri stars have enough total mass to be detected with the NMA. The molecular cloud cores around the embedded sources are moderately extended and dense enough to be detected in CS, while gas disks around the T Tauri are not detected because the radius of such gas disks may be smaller than 70 (50 K/T_{ex}) AU. These results imply that the total amount of matter within the NMA beam size must increase when the central objects evolve into T Tauri stars from embedded sources, suggesting that the compact and highly dense disks around T Tauri stars are formed by the dynamical mass accretion during the embedded protostar phase.

1. Introduction

Recent observations of dust emission and near-infrared excess revealed that many T Tauri stars have compact ($\lesssim$100 AU) and highly dense disks around them (Sargent and Beckwith 1987; Strom *et al.* 1989; Beckwith *et al.* 1990). Theoretical fitting to infrared spectra also required non-spherical structures like disks within a radius of ~100 AU even around embedded sources (Adams, Lada, and Shu 1987; Myers *et al.* 1987). It is, however, not yet clear when and how such compact disks are formed.

We have observed 11 protostellar *IRAS* sources in Taurus in the CS ($J = 2-1$) and 98 GHz continuum emission with the NMA in order to investigate the evolution of compact structures around protostellar sources. Interferometric observations are sensitive only to small scales, so that the confusion from extended foreground and background envelopes is negligible.

2. Results

The results of our observations are summarized in Table 1. We achieved the spatial resolutions of 2.6″–8.8″, corresponding to 360 AU–1200 AU at a distance of 140 pc to

E. Falgarone et al. (eds.), Fragmentation of Molecular Clouds and Star Formation, 353–356.

Table 1. Observations with the NMA

Observed Source	Optical Appearance	$\log[F_{12}/F_{25}]$	L_{IR} ($L_\odot$)	Continuum (mJy)	CS(J=2–1) (Jy km s^{-1})
L1551-IRS5	invisible	−1.02	25	130	15
L1489	invisible	−0.64	3.5	< 9.6	5.6
04361+2547	invisible	−1.02	3.0	< 14	1.4
04368+2557	invisible	< −0.47	1.8	< 11	11
04169+2702	invisible	−0.84	1.1	< 14	2.6
04108+2803	invisible	−0.65	0.68	< 21	1.4
HL Tau	visible	−0.48	6.0	74	< 0.56
DG Tau	visible	−0.32	3.8	57	< 0.39
FS Tau	visible	−0.42	0.66	< 11	< 0.34
GG Tau	visible	−0.11	0.39	41	< 0.44
DL Tau	visible	−0.14	0.23	23	< 0.37

Taurus. The sample consists of 6 embedded *IRAS* sources and 5 visible T Tauri stars. The embedded sources tend to have colder color between 12 and 25 μm than the visible T Tauri stars, as was pointed out by Beichman *et al.* (1986). Observed 98 GHz continuum fluxes are consistent with the broad band spectra of dust emission, indicating that the 98 GHz continuum is the thermal emission from dust grains (Adams, Emerson, and Fuller 1990; Keene and Masson 1990).

Figures 1 shows the 98 GHz continuum maps. The continuum emission was detected toward 4 T Tauri stars and one embedded source, L1551-IRS5. The maps show quite compact sources not resolved by our spatial resolution, being consistent with the continuum emission arising from disks whose radii are less than 100 AU (Beckwith *et al.* 1990; Adams, Emerson, and Fuller 1990). The mass of these dust disks is estimated to be 1.6×10^{-1}–2.9×10^{-2} $M_\odot$under the assumption of the $\kappa_\nu \propto \nu^1$ emissivity law. The density in such disks is extremely high. For example the lower limit to the H_2 number density in the dust disks is estimated to be several times 10^9 cm^{-3} assuming the emitting region to be a sphere of 100 AU in radius.

Figures 2 shows the CS ($J = 2-1$) maps. In contrast with the continuum emission, CS emission was detected toward all the embedded sources, while no visible T Tauri star shows significant CS emission. The CS maps are extended with their FWHM sizes being ~1500–2000 AU.

The lower limit to the gas mass in the CS envelopes is estimated to be 1.8×10^{-2}–1.7×10^{-3} $M_\odot$, assuming the optically thin CS emission with T_{ex}=10 K. The upper limit to the gas mass within the NMA beam size is 1.5×10^{-2} $M_\odot$(see Discussion). The H_2 number densities are thus larger than 10^5–10^6 cm^{-3}, if the emitting region is a sphere of 1500 AU in diameter. The linear size and high density suggest that the observed CS envelopes are very inner part of the extended molecular cloud cores.

3. Discussion

The remarkable point of the present results is that there is a clear difference between the embedded sources and visible T Tauri stars: the visible T Tauri stars are predominantly detected in the continuum emission which arises from the dense disks in the vicinity of stars, while the embedded objects are only detected in CS whose emission comes from the inner portion of molecular cloud cores. This indicates that the embedded sources do not

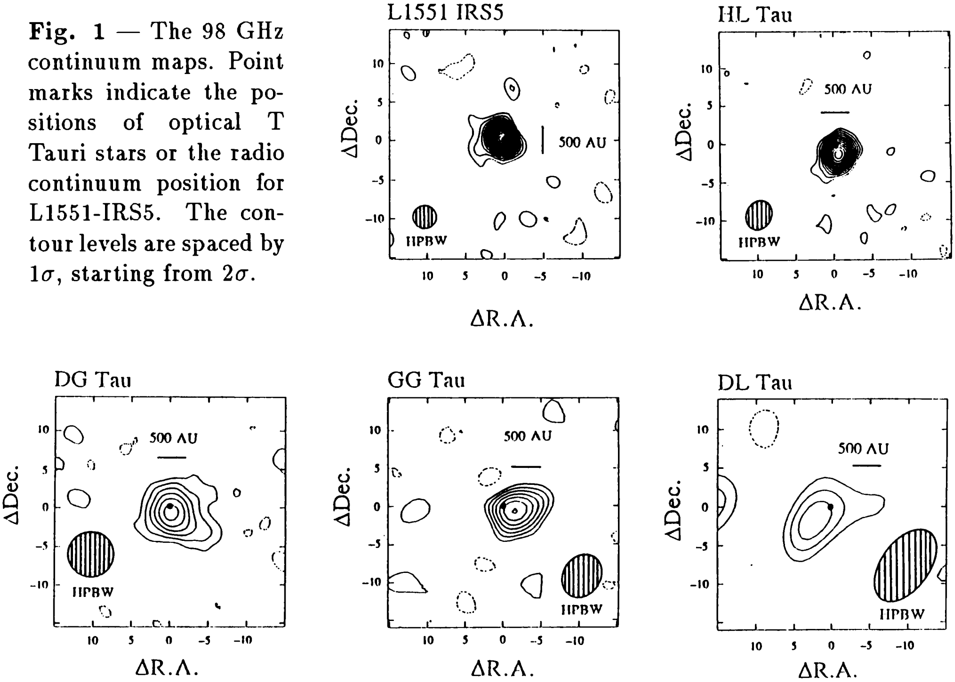

Fig. 1 — The 98 GHz continuum maps. Point marks indicate the positions of optical T Tauri stars or the radio continuum position for L1551-IRS5. The contour levels are spaced by 1σ, starting from 2σ.

have the central mass concentration large enough to be detected in the 98 GHz continuum, while the visible T Tauri stars and L1551-IRS5 do.

For example, let us consider the following 2 cases. Most of the mass around the embedded sources may be widely distributed in their extended envelopes with sizes ~0.01 pc–0.1 pc. Thus we assume a spherical envelope with the size, mass, and density profile of 0.1 pc, 1 $M_\odot$, and r^{-2}, respectively, for embedded sources, then the total gas mass within a radius of 500 AU is only 2.5×10^{-2} $M_\odot$. The 98 GHz continuum emission from such a region is close to our sensitivity of ~12 mJy (3σ), corresponding to 1.5×10^{-2} $M_\odot$, and is rather difficult to be detected with high significance. On the other hand, a disk whose radius and mass are 100 AU and 0.1 $M_\odot$, respectively, produce the 98 GHz continuum emission enough to be detected by the 1000 AU beam. Total mass within the NMA beam size for disks around T Tauri stars is larger than that for embedded sources, so that the 98 GHz continuum emission is detected only toward T Tauri stars. Hence the detection of the 98 GHz continuum emission depends on how much mass is contained within the NMA beam size.

The CS emission is detected only toward embedded sources, because for those objects the detectable CS emission easily arises from the moderately extended envelopes with sizes ~1500–2000 AU. The non-detection of the CS emission toward visible T Tauri stars sets an important upper limit to the size of gas disks if we consider that the CS emission was not detected because the beam averaged gas column density is not large enough as a result of beam dilution. The upper limit to the radius of gas disks is then 70 AU for the assumed excitation temperature of 50 K.

https://doi.org/10.1017/S007418090019905X Published online by Cambridge University Press

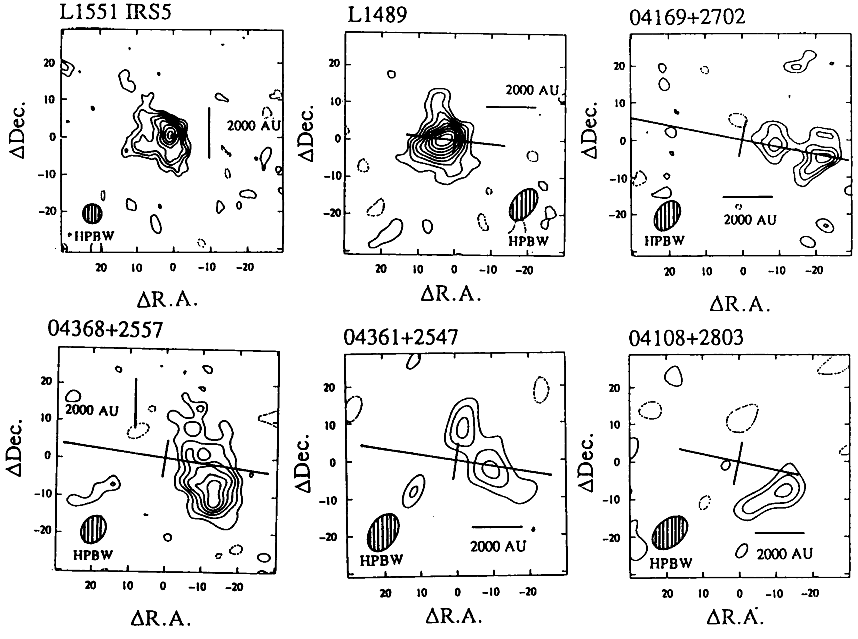

Fig. 2 — The CS ($J = 2 - 1$) maps. The contour levels are spaced by 1σ, starting from 2σ. Plus marks indicate the positions of *IRAS* sources.

We conclude from the above results that the embedded objects in the younger evolutionary phase do not have enough mass concentration to be detected with the NMA beam size of ~500 AU around the central objects, although they have extended massive envelopes with steep density gradient toward the center, and that the more evolved T Tauri stars have enough amount of material to be detected within the ~500 AU radius beam. This suggests that such mass concentration in disks around T Tauri stars occurs through the dynamical mass accretion in the embedded phase of evolution. This result would provide important evidence that embedded sources are accreting protostars.

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