Evolution of Disks in the Course of Star Formation

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Abstract

Observations of circumstellar disks with Nobeyama Millimeter Array (NMA) are presented for the following two topics. The first one is on the continued NMA survey for 13 complete samples of protostar candidates associated with Taurus molecular cloud. The observation confirmed the previous result that protostar candidates do not have detectable 3 mm continuum emission except for the two sources L1551-IRS5 and IRAS 04365+2535. This sets the upper limit to the circumstellar disk mass to be $\sim 0.03\,M_\odot$ for the protostar candidates. The disk mass for protostar candidates tends to be smaller than that around young T Tauri stars, suggesting that it may increase in the course of evolution from protostars into T Tauri stars. The second topic is on the detection of CO (J=1–0) emission toward GG Tau. The observations with the 45-m telescope and with NMA show strong evidence of the CO emission arising from a rotating disk with its size significantly extended with respect to the dust disk. Depletion of CO gas in the GG Tau disk is discussed.

1. Introduction

Observations in millimeter, infrared, and optical wavelengths in 1980's have revealed evidence of circumstellar dust disks around T Tauri stars (Rucinski 1985; Adams, Lada, & Shu 1987; Appenzeller et al. 1984; Edwards et al. 1987; Bertout 1989). Such disks are believed to be protoplanetary disks, since their mass and size, $\sim 0.01\,M_\odot$ and $\lesssim 100$AU, respectively (Beckwith et al. 1990), are similar to those of the minimum mass solar nebula (Hayashi, Nakazawa, & Nakagawa 1985).

Evolutionary studies of circumstellar disks based on statistical analyses play major roles in understanding the formation process of planetary systems. Beckwith et al. (1990) made a 1.3 mm survey observation for dust disks toward 86 T Tauri stars associated with Taurus molecular cloud. They found that the disk mass does not decrease in 10^7 yr, suggesting that the outer part of disks are stable during at least 10^7 yr. The inner part of disks may, however, disappear at a time scale of 3×10^6 yr, as was suggested by the rapid decrease in near- and midinfrared excess emissions toward T Tauri stars with their ages of $\sim 3\times 10^6$ yr (Strom et al. 1989; Skrutskie et al. 1990). While the dissipation process of disks can thus be traced with the aid of age information of T Tauri stars, their formation process may be observed in the course of evolution from embedded protostars into T Tauri stars. For this purpose, it is important to compare the circumstellar mass distribution between protostellar objects and T Tauri stars. I will introduce, as a first topic of this article, a survey observation toward 13 complete samples of *IRAS* selected protostar candidates in Taurus. The results suggest that protostar candidates, on average, do not have circumstellar mass distribution as highly concentrated as T Tauri stars.

Another important topic that I will describe here is the gas associated with protoplanetary disks. Although great efforts have so far been made to detect gas component in protoplanetary

disks, very few sources such as HL Tau show evidence of gas disks with ∼100 AU in size (Sargent and Beckwith 1991). Detection of gas emission from circumstellar disks is difficult not only because line emissions from such disks are weak but they are contaminated by strong background and/or foreground emissions arising from ambient molecular gas. Suppose observing the CO (J=1–0) emission from a gas disk of ∼100 AU in radius at the distance of the Taurus cloud with the 45-m telescope, we would obtain an antenna temperature of ≲50 mK (Omodaka et al. 1992); it must be impossible to detect the line emission with 10-m class telescopes because the intensity becomes more than 10 times less than this. A weak emission line of ∼50 mK can, however, be detected if there would be no background or foreground emission typically of 1–10 K in the Taurus cloud. It is therefore crucial to find T Tauri stars with very low background or foreground CO emission, although it is rare to find such T Tauri stars. GG Tau is a good example of no ambient ^{12}CO emission when observed with the FCRAO 14-m telescope (Skrutskie et al. 1993). One may consider that emission lines of molecules with high critical density would be less contaminated by the foreground and/or background emission, so that those lines would be useful for detecting gas in disks. Such molecular lines may be weaker than the CO lines, because molecules with high condensation temperature are depleted in circumstellar disks as was the case for CS (Blake et al. 1992).

2. Difference in Circumstellar Mass Distribution between Protostars and T Tauri Stars

Ohashi et al. (presented in this colloquium) made a survey observation of protostar candidates and young T Tauri stars in the 3 mm continuum and CS (J=2–1) line emissions with NMA. Protostar candidates are the *IRAS* sources satisfying the following conditions: (1) they are not visible on *Palomar Observatory Sky Survey*, and (2) they show *IRAS* colors cooler than those of T Tauri stars (Beichman et al. 1986). Details of the source selection were described by Ohashi (1991), who selected 13 unambiguous candidates for protostars located in the Taurus molecular cloud. They limited their targets only for those sources associated with Taurus molecular cloud. This is because the mass of newly formed stars is within a narrow range (Cohen & Kuhi 1979), so that evolutionary effects may be recognized much easier than in other molecular clouds with stars of wider mass range. After the initial results of the survey for 5 protostar candidates and 6 T Tauri stars were reported (Ohashi et al. 1991), they continued and finished observations of the 13 complete samples of protostar candidates.

Evidence of circumstellar disks around protostar candidates is mentioned below. The evidence is, however, much weaker than that around T Tauri stars; we still do not know the physical properties of disks around protostar candidates. Firstly, Myers et al. (1987) derived a visual extinction of ≲100 mag toward the central light sources of protostar candidates. Since this value was much smaller than that predicted from simple spherical models for protostellar envelopes, namely 10^3–10^4 mag, they claimed that the mass distribution around protostar candidates might not be spherical but probably be disk like within a radius of ∼100 AU from the central sources. Secondly, phenomenological model fits to the spectral energy distribution of protostellar candidates show shortage at the midinfrared wavelength unless extra emissions from substellar temperature material are taken into account. The extra emissions may be originated from circumstellar disks (Adams, Lada, and Shu 1987). Thirdly Cabrit & André (1991) found that low mass protostellar candidates with large 1.3 mm continuum fluxes tend to have well-developed molecular outflows, suggesting that strong outflows are driven by massive accretion disks. This also indicates the presence of disks around protostar candidates, although the actual disk mass around protostar candidates are still unknown.

Interferometric observations are essential to find out the mass distribution at a scale of ≲1,000AU, not only because of their high angular resolutions but because of their sensitivity

Table 1   Results of the NMA survey observations

Observed Sources	Optical Appearance	CS (J =2–1)			98GHz Continuum		
		I_{CS} (Jy kms^{-1})[a]	Size (AU)[b]	M (M$_\odot$)[c]	F_v(mJy)[a]	Size (AU)[b]	M (M$_\odot$)
L1489	invisible	5.6±0.32	2000×1700	1.1×10^{-1}	<9.6		<2.2×10^{-2}
04108+2803	invisible	1.4±0.32	2700×1200	2.6×10^{-2}	<21		<4.7×10^{-2}
04154+2823	invisible	<0.44			<19		<4.4×10^{-2}
04169+2702	invisible	2.6±0.32	1600×1500[d] 2000×1200[d]	4.9×10^{-2}	<14		<3.2×10^{-2}
04191+1523	invisible	0.80±0.085	1400×1400	1.5×10^{-2}	<9.0		<2.1×10^{-2}
04239+2436	invisible	1.4±0.066	2400×2100	2.6×10^{-2}	<12		<3.2×10^{-2}
04248+2612	invisible	1.7±0.17	2400×2100	4.3×10^{-2}	<12		<3.4×10^{-2}
04295+2251	invisible	<0.56			<21		<2.8×10^{-2}
L1551-IRS5	invisible	15±0.32	2300×1600	2.8×10^{-1}	131±4.0	<430×360	7.0×10^{-2}
04325+2402	invisible	0.85±0.080	1800×1400	1.6×10^{-1}	<9.2		<2.1×10^{-2}
04361+2547	invisible	1.4±0.32	2100×1500[d] 2100×1500[d]	2.6×10^{-2}	<14		<3.2×10^{-2}
04365+2535	invisible	2.5±0.095	1600×1600	4.6×10^{-2}	30±3.8	<940×700	6.8×10^{-2}
L1527	invisible	11±0.32	2600×2000	2.1×10^{-1}	<11		<2.5×10^{-2}
FS Tau	visible	<0.34			<11		<4.1×10^{-2}
T Tau	visible	<0.60			56±10	<550×420	1.0×10^{-1}
DG Tau	visible	1.4±0.32	1600×730	2.6×10^{-2}	57±4.0	<800×770	1.0×10^{-1}
HL Tau	visible	1.5±0.32	1200×850	2.8×10^{-2}	74±4.0	<530×420	1.5×10^{-1}
GG Tau	visible	<0.44			41±4.0	<780×670	1.6×10^{-1}
DL Tau	visible	<0.37			23±4.0	<1470×880	1.0×10^{-1}

[a] Upper limit values are 3σ and errors are 1σ
[b] FWHM size
[c] Gas mass was derived under the assumption of optically thin CS emission
[d] Two spatially separate components are identified

only to the structures less than their resolving-out limits. With Nobeyama Millimeter Array, we can achieve an angular resolution of ~2″, corresponding to the linear scale of ~300 AU at a distance to the Taurus cloud. On the other hand, spatial structures with angular extents larger than 40″ (~5,000AU) are resolved out at 100 GHz, since the minimum baseline length of NMA is 15 m. Hence we can probe only the very inner part of protostellar envelopes without being affected by a large amount of matter extended around them as associated dense cores (Myers, Benson, and Linke 1983; Beichman et al. 1986).

Table 1 summarizes the observations so far made toward 13 complete samples of protostar candidates and 6 young T Tauri stars. The fifth column shows the gas mass contained in each CS emitting area derived under the assumption of optically thin CS emission. This mass actually gives a lower limit to the gas mass because the CS emission is optically thick. The last column lists the total gas mass within the beam size derived from the dust continuum flux under the assumption that the gas to dust mass ratio is 100, that the power law index of grain emissivity is 1, and that the temperature of the 3 mm emitting regions is 30 K for most cases. Details of the mass derivation are described in Ohashi et al. (1991).

The CS emission is extended over 1,000–2,000 AU around or near the central objects. Protostar candidates are associated with extended envelopes of ~10,000 AU in radius. Hence the extended CS emission arises from very inner part of such envelopes; most of the emission contained in outer envelopes was completely resolved out by the present interferometric observations. The CS emission does not spatially coincide with stellar positions for the 3 protostar candidates 04108+2803, 04248+2612, and 04361+2547. This is caused probably because the optically thick CS (J=2–1) emission does not follow the actual mass distribution around those sources with bad positional coincidence. For the case of 2 T Tauri stars DG Tau and HL Tau detected in CS, the CS emission does not coincide with their stellar positions, either. Small visual extinctions (a few mag) toward these T Tauri stars suggest that we would have detected the CS emission directly associated with the circumstellar disks around them without contamination from foreground or background CS emission, if the CS disks had a
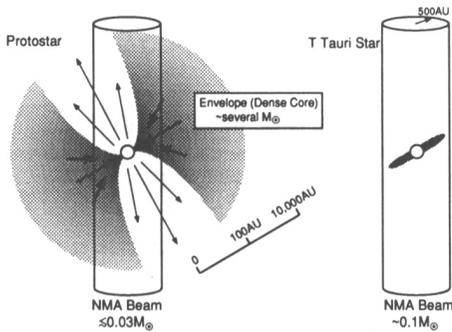
size of ~70AU or more. No detectable CS emissions directly associated with the stars implies that CS molecules may be depleted in their disks, as was suggested for HL Tau by Blake, van Dishoeck, & Sargent (1992).

The 98 GHz continuum emission was detected from 2 out of 13 protostar candidates, L1551-IRS5 and 04365+2535, and from 5 out of 6 T Tauri stars. The emission size was not resolved by the NMA beam of ~500 AU in radius; the continuum emission is consistent with arising from compact dust disks around these objects. It is remarkable in Table 1 that only two protostar candidates showed detectable continuum emission, whereas most of the T Tauri stars were detected in the continuum. Because we selected T Tauri stars with strong 1.3 mm and 100 µm fluxes, it is reasonable that most of them also h⋅ ⋅⋅ strong 3 mm flux from dust disks; the high detectability of the continuum emission toward T Tauri stars may be a selection effect. On the other hand, the small detectability toward protostar candidates are real since we observed all the protostar candidates selected under the definite criteria. The upper limit to the total mass within the beam size of ~500 AU is typically $0.03\,M_\odot$ for protostar candidates if we assume similar disk temperature for protostar candidates as for T Tauri stars.

The difference in the 98 GHz continuum and CS line detectabilities between the two types of objects is attributable to the difference in circumstellar mass distribution between them, as is schematically illustrated in Figure 1. The protostar candidates tend to have large mass at 1,000–2,000 AU in radius or at larger radii, while they do not have so much mass within a radius of 500 AU as T Tauri stars do. This may indicate that many protostars in Taurus have disk mass smaller than the present upper limit of $0.03\,M_\odot$. Such small mass in the protostellar phase is consistent with the relatively small luminosity of protostar candidates in Taurus and agrees well with current theories on steady formation of star/disk systems (Stahler, Shu, and Taam 1980; Nakamoto and Nakagawa 1993). The disk mass around protostars increases with the evolution of protostars into T Tauri stars.

3. A Gas Disk associated with GG Tau

Figure 2 shows the ^{12}CO ($J=1$–0) line profile detected toward GG Tau and the negative result for the $C^{18}O$ ($J=1$–0) emission (Skrutskie et al. 1993). The ^{12}CO emission was detected with ~0.4 K in antenna temperature, while it was not detected with the upper limit of 50 mK with the FCRAO 14-m telescope, which has ten times larger beam solid angle than the 45-m telescope. This means that the CO emission detected with the 45-m telescope must be compact and be directly associated with GG Tau. The double peaked CO emission profile is well fitted by a disk model with ~500 AU in radius.

Figure 3 shows the channel maps of ^{12}CO ($J=1$–0) emission toward GG Tau observed with NMA (Kawabe et al. 1993). The CO maps show shift in the emission peak from east
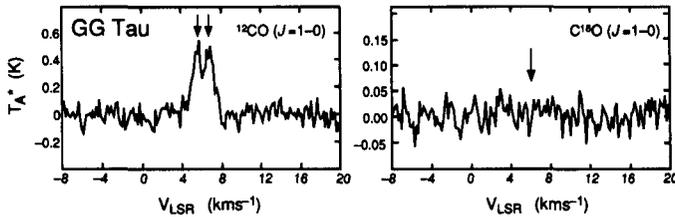
**Figure 2** ^{12}CO and C^{18}O data obtained with the 45-m telescope (Skrutskie et al. 1993)

to west with increasing velocity from 5.7 to 7.3 kms^{-1}, being consistent with a rotating gas disk model with the radius and rotational velocity of 500 AU and 0.8 kms^{-1}/sin i, respectively. Integrating the channel maps over the emission velocity width, we obtain the total CO intensity map elongated in the northwest to southeast direction with the size of $10'' \times 6''$ (1,400 AU×840 AU). The integrated CO map shows the similar morphology and position angle to the IRAM 2.6 mm continuum map (Simon and Guilloteau 1993). Although the size of the CO emission is approximately twice as large as that of the continuum, this is natural because the CO emission arises from less dense outer regions compared to the continuum emission as a result of the higher mass emissivity for CO than for continuum.

The NMA map of ^{12}CO (J=1–0) agrees sufficiently well with the ^{13}CO (J=1–0) map obtained at OVRO (presented by Dr. A. Sargent in this colloquium). She suggested, however, that the actual gas disk would be elongated in the north-south direction based on the ^{13}CO (J=2–1) observations at OVRO (see the discussion following this paper). For the purpose of understanding the gas disk around GG Tau, we must wait for further observations with higher sensitivities and spatial resolutions so that we can resolve the spatial and velocity structure of the gas emission associated with GG Tau (see Dutrey, Guilloteau, & Simon 1994).

A very important conclusion derived from the negative result for the C^{18}O line shown in Figure 2 is the depletion of CO gas with respect to dust. Integrating over the velocity width of 2 kms^{-1}, we can set the upper limit to the C^{18}O intensity as 0.11 K kms^{-1}. This gives the total amount of C^{18}O within the beam size 2,000 AU of the 45-m telescope to be less than 7×10^{-9} M$_\odot$. The total mass of dust grains within the NMA beam size is 1.6×10^{-3} M$_\odot$ as was in Table 1 (Note that the total mass of 0.16 M$_\odot$ in Table 1 was obtained by assuming the gas to dust mass ratio of 100). The ratio of C^{18}O mass to the dust mass is hence 4×10^{-6}, which is one order of magnitude smaller than the ratio of 4×10^{-5} calculated with nominal interstellar abundances. Hence the CO gas is significantly depleted with respect to dust.

It might be suggested that C^{18}O was not detected as a result of beam dilution, but not as a result of CO depletion. If optically thick C^{18}O gas would be concentrated within ~70 AU in radius, it would result in no detection of the C^{18}O emission due to beam dilution. However the dust disk around GG Tau has been resolved with the IRAM interferometer to have the size of 500 AU×700 AU (Simon and Guilloteau 1993; Dutrey et al. 1994), so that the beam dilution is not the cause of the non-detection of C^{18}O, if the gas disk has similar size to the dust disk.

The depletion of CO gas with respect to dust means either of the following two cases or both. (1) The fractional abundance of CO relative to H$_2$ in the circumstellar disk of GG Tau is at least 10 times smaller than the ordinary value in molecular clouds. This may suggest that most of CO molecules in the GG Tau disk are significantly depleted onto dust grains. (2) The gas to dust mass ratio is at least an order of magnitude smaller than the ordinary value of 100 for interstellar matter. This case may imply that most of the gas in the disk has already been dissipated. We need quantitative determination of the H$_2$ abundance in T Tauri disks in order to distinguish the two cases.
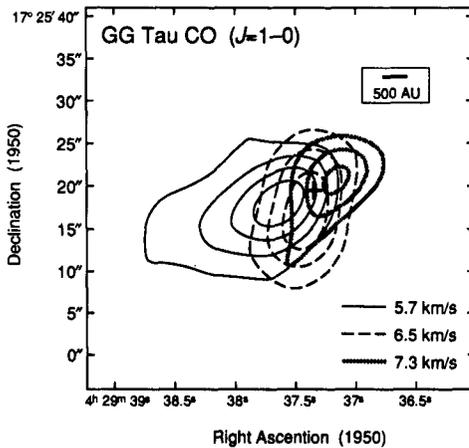
Figure 3 Map of CO (J=1–0) emission observed with NMA (Kawabe et al. 1993)

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DISCUSSION

<u>K. Stapelfeldt</u> For your samples of the embedded objects and the T Tauri stars, have you made a comparison of the continuum detectability at 1.3mm?

<u>M. Hayashi</u> Some of the sources have been observed at 1.3mm, but not so many. Phillipe Andre - who was supposed to be here today - when you see his map in Rho Oph of the embedded objects, they usually have an extended structure. His maps of T Tauri stars show compact structure.

<u>K. Stapelfeldt</u> One reason I think this question is important is that you expect the grain opacity will become less steep - the spectral index will go from 2 to 1 as you evolve in these early stages. The embedded sources may in fact have a different opacity spectral index than for the T Tauri stars, and that could make a factor of 10 difference in the amount of mass you can detect. It could explain the entire detectability difference you see between the two samples.

<u>M. Hayashi</u> It is usually said that the ß index of L1551 IRS5 is greater than 1. When we compare 150 and 100GHz observations from the compact continuum source, we get a spectral index of 1. So I assume that ß must be 1 for all sources.

<u>K. Stapelfeldt</u> It would be nice to know the value of ß for all your sources, if you could get it.

<u>T. Henning</u> What are the selection criteria for IRAS sources?

<u>M. Hayashi</u> Details of the source selection was discussed in Ohashi (1991). Among 1164 sources in the Taurus region listed in the IRAS point source catalog, he first selected 123 sources with significant detection at 3 or 4 wavelength bands including 25 and 60 μm. Excluding cataloged stars, galaxies, sources exhibiting colors of normal stars, and extended sources typical of cirrus emission, he then picked up 46 sources with protostellar characteristics. On the POSS atlas, 13 out of 46 have no optical counterparts, with the other 33 have visible counterparts, many of which were identified as T Tauri stars.

<u>A. Sargent</u> Let me respond to your contention that the 45-meter Nobeyama spectrum and the NMA results conflict with the studies of GG Tau at Owens valley. It is difficult to compare the 45-m. 15" resolution spectral line profile interpretation with our 5"×3" ^{13}CO (J=2-1) images, which show elongated gas extending over 20". It is clear that gas surrounds not just GG Tau, but also its companion system, GG Tau/c. Perhaps mapping around the central GG Tau position with the 45-m would resolve this discrepancy. However, it seems likely that the CO samples the ambient cloud

rather than circumstellar material, since models of disks demonstrate that CO, and even ^{13}CO, emission in the direction of star-disk systems is very optically thick. The fact that our systemic velocity for the GG Tau material differs from the Nobeuama ^{12}CO peak velocity supports this view. Our ^{13}CO (J=2-1) Owens Valley maps show clear evidence of a velocity gradient in our elongated gas structure along a N-S axis joining GG Tau and GG Tau/c. We see at blue-shifted velocities a weak distortion in the elongated structure, consistent with the blue shifted structure seen by Kawabe et al. in ^{12}CO. We do not see the matching redshifted emission expected for rotation about a N-S axis. On the contrary, the bulk of the ^{13}CO (J=2-1) emission (and the ^{13}CO(J=1-0) emission) is confined to the elongated N-S structure. Again we suggest that the optically thick CO emission icludes a large and confusing contribution from the ambient cloud.

M. Hayashi   As I stated in the text, ^{12}CO (J=1-0) emission toward GG Tau was not detected with an upper limit of 50mK by the FCRAO 14-m telescope which had a beam size 3 times larger than the 45-m telescope. NMA detected no significant emission except around GG Tau in spite of its wide field of view of 1'(FWHM). These facts suggest that the ^{12}CO (J=1-0) emission detected toward GG Tau is not much extended compared to the 15" beam of the 45-m telescope and is directly associated with the star/disk system. However we need further observations in order to clarify the true gas distribution atound GG Tau. Observations with the IRAM interferometer and with other molecular lines will solve the present discrepancy between your data and ours.

N. Scoville   It would be interesting to compare the disk axis in GG Tau as derived from optical polarization measurements with that of your mm line disk.

M. Hayashi   Yes, polarization measurements are very important.

S.S. Hayashi   About GG Tau disk, is there any comparison of continuum measurements to deduce dust disk properties, such as the morphology, spectral index, opacity? And any FIR/MIR high resolution measurements? (What is the "real" shape of the disk? Can it be delineated by molecular line observations, or dust continuum better?)

M. Hayashi   You may refer to the papers by Beckwith et al.(1990) and Simon and Guilloteau (1992) as well as Kawabe et al.(1990) for the disk properties and its morphology. No one had directly observed the "real" shape of disks at any wavelength. Disks observed by molecular lines may be larger than those observed by dust continuum, because molecular line emissions are sensitive to much lower column density than the dust emission.