# NMA IMAGING OF ENVELOPES AND DISKS AROUND LOW MASS PROTOSTARS AND T TAURI STARS

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**Abstract.** We are intensively studying low mass star formation with the radio telescopes at Nobeyama in Japan. Using both the Nobeyama 45 m dish equipped with a 2 × 2 array receiver and the Nobeyama Millimeter Array (NMA), we can cover a very wide spatial range from overall molecular clouds down to compact protoplanetary disks. With the 45 m dish we are investigating hierarchical structures of molecular clouds including star-forming cores. With NMA we are imaging disklike structures (i.e., envelopes, accretion disks, and protoplanetary disks) around protostars and T Tauri stars. Recently, we have completed our survey for dense disklike envelopes around eleven Class 0 & I protostars by NMA. In this paper, we will present our recent results of the disklike envelopes in addition to the previous NMA results of the disks around three T Tauri stars. On the basis of the data, we will discuss the evolution of the disklike structures (dense envelopes → tenuous ones → dispersing ones → accretion disks → protoplanetary ones), and propose a new scenario for the formation of low mass stars.

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## 1. Background

In low mass star formation, there are many interesting physical and chemical processes which one should understand. We are now studying or will study some of the processes with the Nobeyama 45 m telescope and the Nobeyama Millimeter Array (NMA).

In molecular clouds (age $\sim 10^7$ yr, size $\sim 10^7$ AU), hierarchical structures generally exist (e.g., Scalo 1985), and the cloud turbulence plays an important role in the hierarchy. In order to reveal the hierarchy, Sunada *et al.* (1997) have mapped the entire region of 1° × 1°.5 of Heiles Cloud 2, the central region of Taurus Molecular Cloud Complex, with a spatial resolution as high as 50" by using the 45 m telescope equipped with a $2 \times 2$ array receiver (Figure 1). It is noted that our homogeneous map covers a wide spatial range from 3 to 0.03 pc, two orders of magnitude! Consequently, we have successfully revealed the cloud hierarchy: six filaments with sizes of $\sim 1 \times 0.4$ pc, five major clumps with sizes of $\sim 0.3 \times 0.1$ pc, and numerous fragments with sizes of $\sim$ 0.03 pc. We should understand these components in connection with the fractal structure found by Larson (1995).

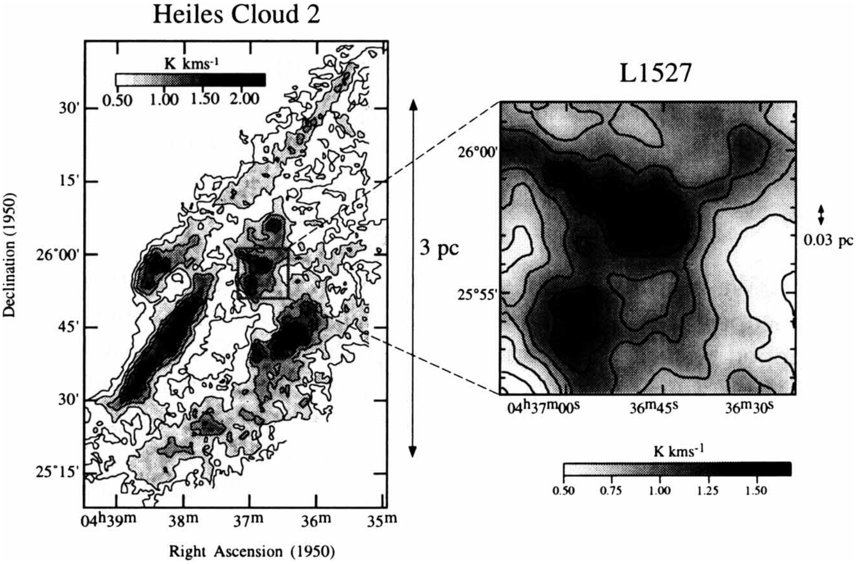

*Figure 1.* $C^{18}O$(1-0) Total Map of Heiles Cloud 2

In the cloud hierarchy molecular cores (age $\sim 10^{5-6}$ yr, size $\sim 10^4$ AU) are the birthplace for new stars. One of the most important properties of the cores is their mass function, directly linked to IMF of stars (e.g., Nakano *et al.* 1995). To obtain the mass function, we need statistical studies of the core formation in the hierarchy as shown in Figure 1. Another important property is how the cores gravitationally collapse to form stars: Shu's solution (Shu 1977) or Larson's one (Larson 1969). The initial conditions of the solutions would be influenced by the turbulence and magnetic fields, which work against gravitation. Therefore, their decay processes are essential for triggering the collapse.

After the gravitational collapse of the cores begins, Class 0 protostars with ages of $\sim 10^4$ yr (e.g., B335 and L1527) are considered to appear at the center of the cores (André *et al.* 1993). The luminosity of the protostars is due to the release of the gravitational energy of infalling gas, and is controlled by the mass accretion rate. In this stage, the formation of disklike envelopes and the ignition of outflows simultaneously occur, and they essentially determine the mass accretion onto the central protostars.

When the major part of the core gas infalls or disperses, the protostars are believed to evolve from Class 0 to Class I with ages of $\sim 10^5$ yr (e.g., L1551 IRS 5 and HL Tau). In this stage the gas in the disklike envelopes is falling onto compact accretion disks and the disks are growing. The infalling motions in the envelopes around L1551 IRS 5 and HL Tau were detected by the NMA imaging observations (Saito *et al.* 1996; Hayashi *et al.* 1993). Recently, Mundy *et al.* (1996) succeeded in imaging directly the compact accretion disk with a radius of 90 - 160 AU around HL Tau.

At the transient stage between the Class I protostars and classical T Tauri stars (CTTSs) with ages of $\sim 10^{5-6}$ yr, there are several flat-spectrum T Tauri stars (e.g., DG Tau and T Tau). It is very important to observe the sources for understanding the evolution from the large envelopes into the compact accretion disks. In the disposal of the envelopes outflow as well as accretion plays an important role. In the disklike envelope around DG Tau, Kitamura *et al.* (1996a) found a dispersing motion which might be driven by the stellar wind. Momose *et al.* (1996) found that the core around T Tau is being dispersed by the outflow. These dispersing processes would determine the star formation efficiency in the cores (Nakano *et al.* 1995).

To understand how the initial conditions for planet building (Cameron 1985; Hayashi *et al.* 1985) are determined during the evolution of the disklike structures, we should observe compact disks around weak-line T Tauri stars (WTTSs) with ages of $\sim 10^{6-8}$ yr as well as CTTSs. The accretion disks around CTTSs are considered to evolve into protoplanetary disks around WTTSs. In fact, the spectral energy distributions (SEDs) towards many T Tauri stars strongly suggest the disk evolution (e.g., Strom *et al.* 1989; Moriarty-Schieven *et al.* 1994). For the two CTTSs of DM Tau and GG Tau, rotating compact disks with a few hundred AU radii have been imaged by NMA (Saito *et al.* 1995; Kawabe *et al.* 1993). However, no one has succeeded in imaging the disks around WTTSs.

## 2. Our Survey

We have completed our survey for the dense disklike envelopes around Class 0 & I protostars with NMA (Saito 1997). The purpose of our study is to understand the formation and evolution of the disklike envelopes around low mass protostars and to reveal the evolution of the protostars. The protostellar evolution from Class 0 to I has already been proposed by André *et al.* (1993) based on SEDs. The profiles of SEDs, however, are very sensitive to viewing angles and do not necessarily represent the evolution, as pointed out by Tamura *et al.* (1996) and Ohashi *et al.* (1997). Therefore, it is worthwhile to re-investigate the evolution from a more physical standpoint.

We have observed ten protostars in Taurus, which are listed in Table 1, in addition to B335. For our survey it is essential to select the best molecular lines, and we selected the $H^{13}CO^+(1\text{-}0)$ line as a high-density tracer. This is because the line is expected to be optically thin (Butner *et al.* 1995), and because the 45 m observations by Mikami (1995, private communication) showed that the $H^{13}CO^+$ emission is distributed more compactly than $^{13}CO(1\text{-}0)$ and $C^{18}O(1\text{-}0)$. Although the CO lines seem good, as shown by Hayashi *et al.* (1993) and Ohashi *et al.* (1996 and 1997), the lines tend to be influenced by outflowing gas because of their low critical densities.

## 3. Results and Discussion

### 3.1. DISKLIKE ENVELOPES AROUND TYPICAL PROTOSTARS, B335 AND L1551 IRS 5

First of all, we will show our results for the typical Class 0 protostar, B335, and the typical Class I protostar, L1551 IRS 5. In B335, Chandler *et al.* (1993) imaged an elongated core perpendicular to the molecular bipolar outflow along the east-west line. The protostellar collapse has been suggested by Zhou *et al.* (1993). They showed that velocity profiles of several molecular lines agree with the inside-out collapse model proposed by Shu (1977). At NMA we have imaged an infalling disklike envelope with a radius of $\sim 2000$ AU, whose major axis is perpendicular to the outflow axis (Saito *et al.* 1997). The total flux of $H^{13}CO^+$ and the 87 GHz continuum flux density were 1.3 Jy km $s^{-1}$ and 18 mJy, respectively, and the mass of the envelope is estimated to be 0.06 $M_\odot$. We have detected velocity shifts along both the disk minor and major axes, which can be interpreted as infalling and rotating motions, respectively. The infall velocity and the mass accretion rate are estimated to be 0.14 km $s^{-1}$ at $r = 2200$ AU and $1.2 \times 10^{-6} M_\odot yr^{-1}$, respectively. The presence of the infall is supported by the small rotational velocity of 0.14 km $s^{-1}$ at $r = 490$ AU, only one third of the Kepler velocity. The infall velocity, however, is smaller than the free-fall velocity toward the protostar with 0.1 $M_\odot$, and the calculated accretion luminosity is also smaller than the actual luminosity. Our model calculations show that the differences are partly due to a finite beam, a finite velocity resolution, and the uncertainty of the disk thickness, the disk inclination angle, and the stellar mass.

With the Nobeyama 45 m telescope, we have also investigated 10000 AU-scale structures including the 1000 AU-scale envelope in order to study the initial conditions of the B335 core before the gravitational collapse. We have obtained a density profile obeying a power law of $r^{-1.85}$, and the coefficient of the profile is slightly larger than that expected in a hydrostatic isothermal core. Furthermore, we have found a velocity gradient along the line parallel to the major axis of the envelope, suggesting rigid rotation with an angular velocity of $1.1 \times 10^{-14}\mathrm{s}^{-1}$. Consequently, it is possible that the protostar in B335 has been formed in a rigidly rotating isothermal core.

Many authors have studied L1551 IRS 5 as a prototype of protostars. Sargent *et al.* (1988) revealed a disklike envelope with 700 AU radius, which is perpendicular to the molecular outflow. Ohashi *et al.* (1996) recently suggested possible infall in a $^{13}$CO disklike envelope observed by NMA. By the H$^{13}$CO$^+$ NMA observations, we have imaged an infalling disklike envelope with a radius of 2800 AU and a mass of 0.27 $M_\odot$, the major axis of which is perpendicular to the outflow axis (Saito *et al.* 1996). In the envelope, we have detected probable infall and slow rotation. The infall velocity and the mass accretion rate are estimated to be 0.6 km s$^{-1}$ at $r = 800$ AU and $1.1 \times 10^{-5} M_\odot \mathrm{yr}^{-1}$, respectively. The rotational velocity of 0.23 km s$^{-1}$ at $r = 900$ AU is smaller than the Kepler velocity, which fact is consistent with the presence of the infall. The infall velocity is smaller than the free-fall velocity toward the 1 $M_\odot$ object, which is similar to the B335 case. The accretion luminosity, however, is four times larger than the actual luminosity, that is the luminosity problem.

### 3.2. NEW SCENARIO FOR EVOLUTION OF DISKLIKE ENVELOPES AROUND PROTOSTARS

Our NMA imaging of the dense envelopes around the Class 0 & I protostars is shown in total maps of Figure 2 (Saito 1997). For the sources with intense H$^{13}$CO$^+$ emission, dense disklike envelopes are clearly seen, while for the other sources envelopes can not be well recognized. To discuss these maps together with other important properties, we summarize significant parameters including our data of the H$^{13}$CO$^+$ total fluxes and the 87 GHz continuum flux densities in Table 1 (Saito 1997).

Our results of the H$^{13}$CO$^+$ imaging can be explained in terms of the evolution of the envelopes, as follows. (1) The H$^{13}$CO$^+$ emission was detected for some sources and not detected for the other sources, while CO

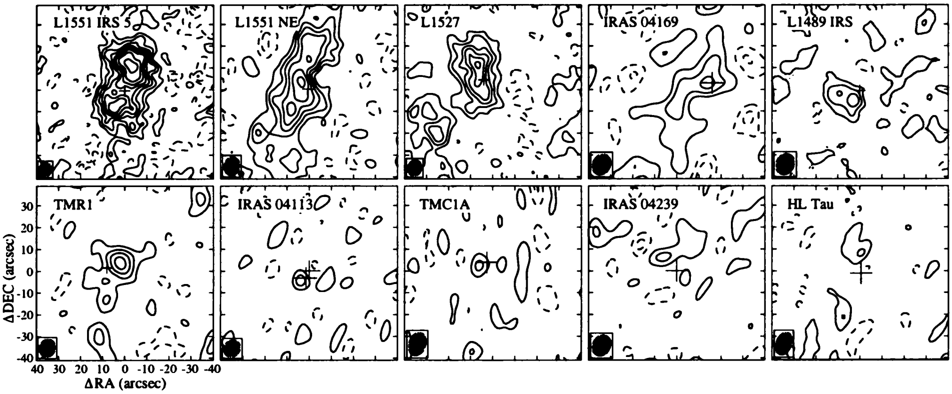

*Figure 2.* $H^{13}CO^+$(1-0) Total Maps of 10 Protostars in Taurus

TABLE 1. Properties of Protostars

| Source Name | $H^{13}CO^+$(1-0) total flux (Jy km $s^{-1}$) | CO disk? | CS(5-4) wing emission? | at the center of an $H^{13}CO^+$ parent core? | $T_{bol}$ (K) | 87 GHz flux density (mJy) | CLASS |
|---|---|---|---|---|---|---|---|
| L1551 IRS 5 | 7.3 | $C^{18}O^a$ | Y | $Y^g$ | 97 | 74 | E |
| L1551 NE | 5.7 | $C^{18}O^b$ | Y | --- | 75 | 63 | E |
| L1527 | 3.3 | $C^{18}O^c$ | Y | $Y^g$ | 59 | 22 | E |
| IRAS 04169 | 2.7 | $C^{18}O^d$ | Y | $Y^g$ | 170 | < 26 | E |
| L1489 IRS | 1.5 | $C^{18}O^d$ | Y | --- | 238 | < 18 | F |
| TMR1 | 0.52 | $^{13}CO^e$ | Y | $N^h$ | 144 | < 28 | F |
| IRAS 04113 | (0.09) | --- | N | --- | 606 | 52 | G |
| TMC1A | (0.07) | $^{13}CO^d$ | N | $N^h$ | 172 | < 23 | G |
| IRAS 04239 | < 0.1 | --- | N | --- | 236 | < 24 | G |
| HL Tau | < 0.1 | $^{13}CO^f$ | --- | --- | 576 | 44 | G |

CO disk : a. Sargent *et al.* (1988), b. Momose (1997, private communication), c. Ohashi *et al.* (1997)
d. Ohashi (1997, private communication), e. Terebey *et al.* (1990), f. Hayashi *et al.* (1993)
CS wing : Moriarty-Schieven *et al.* (1995)
$H^{13}CO^+$ parent core : g. Mizuno *et al.* (1994), h. Takakuwa (1996)
$T_{bol}$ : Chen *et al.* (1995)

disks seem to exist in all the sources. This fact directly shows the density evolution of the envelopes. (2) The detection of the CS(5-4) wing emission is well correlated to the detection of the $H^{13}CO^+$ emission. This fact also supports the density evolution in the envelopes, because the CS wing emission is considered to represent the interaction between the dense gas of parent cores and outflows. Note that no detection of the wing emission does

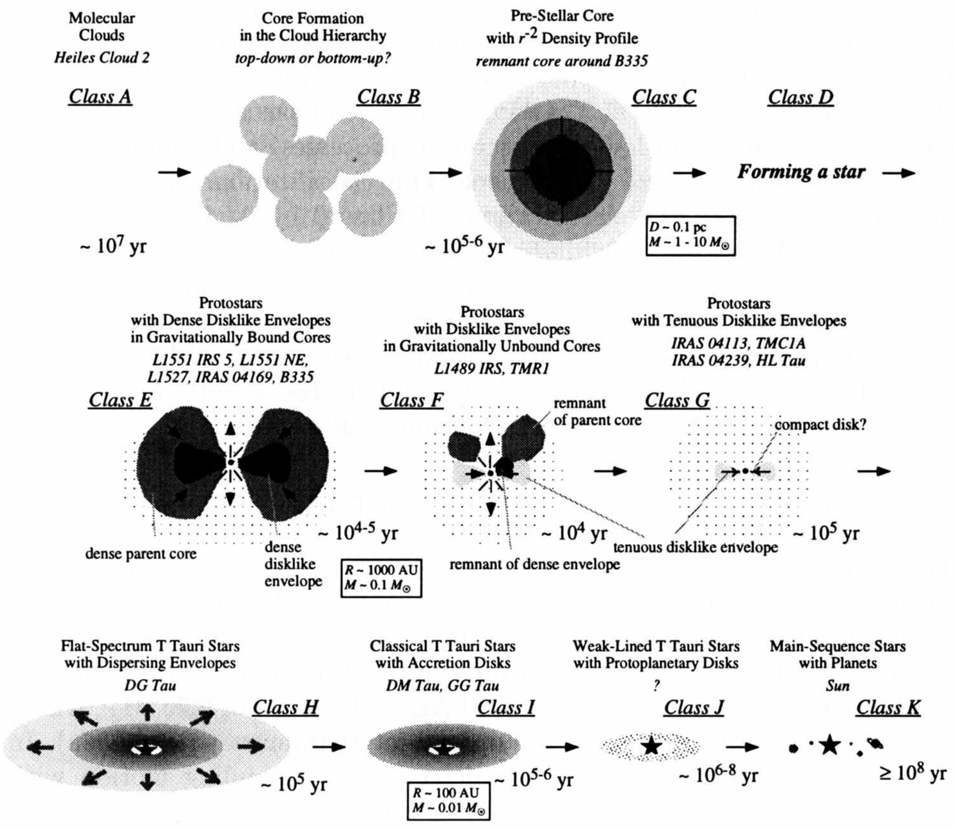

*Figure 3.* Our Proposed Scenario for Low Mass Star Formation

not indicate the termination of the outflows, because the outflow phenomena are seen all over the sources. (3) It is natural that the association with dense parent cores is correlated with the presence of the dense envelopes. (4) Although the bolometric temperatures estimated by Chen *et al.* (1995) tend to increase from the top to bottom in Table 1, there is no clear correlation between the $H^{13}CO^+$ intensities and the temperatures. This is because the temperatures derived from SEDs are sensitive to the geometrical factor of viewing angles rather than the protostellar evolution. (5) We can find no clear correlation between the 87 GHz continuum flux densities and the $H^{13}CO^+$ total fluxes. In addition, the submillimeter continuum flux densities at 264 GHz (Moriarty-Schieven *et al.* 1994) do not correlate with the $H^{13}CO^+$ fluxes. The continuum flux densities would not be good indicators for the protostellar evolution, because the emission comes not only from the envelopes but also from the accretion disks.

According to the above discussion, we propose a new scenario for the evolution of the disklike envelopes around protostars during low mass star formation, as schematically shown in Figure 3. We divide protostars into the three classes of *Class E*, *F*, and *G*: Dense envelopes evolve into tenuous envelopes owing to outflow and accretion processes, and simultaneously, dense parent cores accrete and disperse. Our classification is considered to be better than both the classifications of Class 0 by André *et al.* (1993) and $T_{\mathrm{bol}}$ by Myers *et al.* (1993). This is because the discrimination between protostars with and without gravitationally bound parent cores is physically clearer than that based on SEDs which are sensitive to viewing angles. It is very important to know whether a parent core surrounding a star is gravitationally bound or not, because the stellar mass is determined by the supply of gas from the bound core (Nakano *et al.* 1995).

### 3.3. COMPACT DISKS AROUND CLASSICAL T TAURI STARS

The envelope evolution newly found by us can be consistently connected with the disk evolution revealed by the previous NMA imaging of the disks around the three CTTSs of DG Tau, DM Tau, and GG Tau, as shown in Figure 3. For DG Tau, a flat-spectrum T Tauri star, we imaged a dispersing disklike envelope with a radius of 2800 AU and a mass of 0.03 $M_{\odot}$, whose major axis is perpendicular to the optical jet (Kitamura *et al.* 1996a). In the outer part of the envelope, we detected an expanding motion with a velocity of 1.5 km $s^{-1}$. The expansion velocity is larger than both the Kepler and free-fall velocities, and the expansion could be driven by the stellar wind from an energetic point of view. Since DG Tau is now evolving into a CTTS from a protostar, the star can be considered as *Class H* in our scenario: The envelope is disappearing and a compact accretion disk will remain. Recently, Kitamura *et al.* (1996b) have succeeded in imaging the accretion disk with a radius of $\sim$ 100 AU around DG Tau by achieving the highest spatial resolution of one arcsec in NMA. This study revealed that almost all the mm flux density at 147 GHz is coming from the compact disk and that the contribution of the envelope to the SED is negligible.

For the two CTTSs of DM Tau and GG Tau, rotating compact disks with radii of 350 and 500 AU, respectively, were imaged by NMA (Saito *et al.* 1995; Kawabe *et al.* 1993). The rotation roughly agrees with Kepler rotation. Although GG Tau is a binary system, both the stars can be regarded as *Class I* in our scenario: A compact accretion disk is rotating around a central star and will evolve into a protoplanetary disk.

In order to reveal the initial conditions for planet formation, we should accurately estimate the disk properties independently of instrumental parameters. For the disk around DM Tau, we have performed radiative transfer calculations including the observational parameters, based on a Kepler rotating disk (Kitamura *et al.* 1993), and have applied the calculations to the observed data. The fitting is quite good as shown in Figure 4. The model parameters are as follows: $\Sigma(r) = 0.02(r/R)^{-2}\mathrm{gcm}^{-2}$, $T(r) = 30(r/R)^{-0.5}\mathrm{K}$, $R = 350\mathrm{AU}$, $i = 40°$, $M_* = 0.48M_\odot$, (beam size) $= 6".5 \times 4".9$, and (velocity resolution) $= 0.81$ km s$^{-1}$. The disk mass is calculated to be 0.02 $M_\odot$, which supports the minimum-mass nebula proposed by Hayashi *et al.* (1985). Here we assume no condensation of CO on grains. The power law index of $\Sigma(r)$ was estimated to be 2 by Saito *et al.* (1995), which index is larger than the value of 1.5 in the Hayashi model.

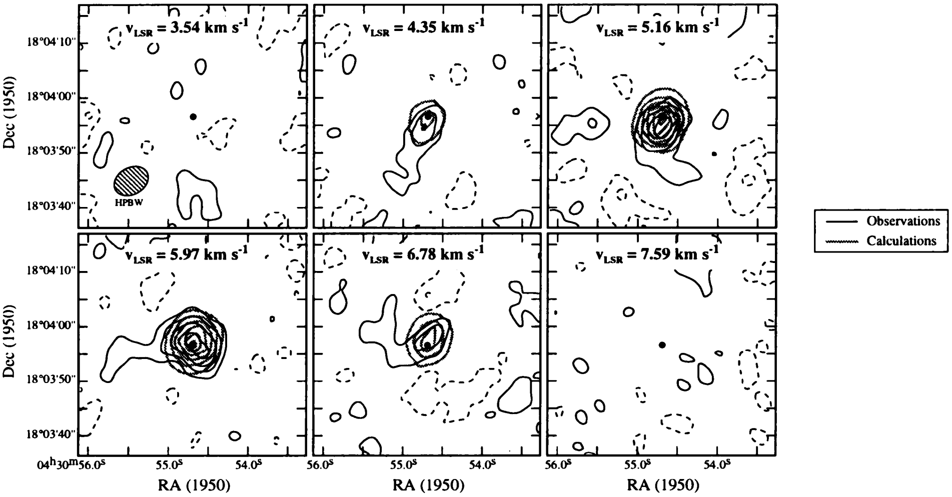

*Figure 4.* Model Fitting to $^{12}$CO(1-0) Channel Maps of DM Tau

## 4. Our Future Studies

1. To understand the hierarchy of molecular clouds including star-forming cores, we will efficiently perform large-scale and high-resolution mapping for several clouds with the Nobeyama 45 m telescope equipped with a new 5 × 5 array receiver.
2. To check the generality of our proposed scenario, we should increase our sample number of NMA imaging in each evolutionary stage of low mass star formation. The sensitivity and spatial resolution of NMA will be improved by incorporating the 45 m dish into the array (*Rainbow project*) and by a phase correction method, respectively.
3. To reveal planet formation, we will directly image planet-forming regions around T Tauri stars by the Large Millimeter and Submillimeter

Array (LMSA) in Chile in 2000's. The spatial resolution of LMSA will reach 0.01 arcsec, that is 1.4 AU at the distance of Taurus!

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