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N_2H^+ OBSERVATIONS OF MOLECULAR CLOUD CORES IN TAURUS

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ABSTRACT

We report the millimeter-wave radio observations of molecular cloud cores in Taurus. The observed line is the N_2H^+ emission at 93 GHz, which is known to be less affected by molecular depletion. We have compared starless (IRAS-less) cores with star-forming cores. We found that there is no large difference between starless and star-forming cores, in core radius, linewidth, core mass, and radial intensity profile. Our result is in contrast with the result obtained by using a popular molecular line, in which starless cores are larger and less condensed. We suggest that different results mainly come from whether the employed molecular line is affected by depletion or not. We made a virial analysis, and found that both starless and star-forming cores are not far from the critical equilibrium state, in Taurus. Together with the fact that Taurus cores are almost thermally supported, we conclude that starless Taurus cores evolve to star formation without dissipating turbulence. The critical equilibrium state in the virial analysis corresponds to the critical Bonnor-Ebert sphere in the Bonnor-Ebert analysis (Nakano 1998). It is suggested that the initial condition of the molecular cloud cores/globules for star formation is close to the critical equilibrium state/critical Bonnor-Ebert sphere, in the low-mass star forming region.

Key words : ISM:clouds — ISM:individual (L1521F, K1527, L1551, Taurus Cloud Complex) — ISM: molecules — ISM: structure — radio lines: ISM — stars: formation

I. INTRODUCTION

The molecular cloud core is the site for star formation and is the material of the star and the planetary system. The core is thought to be supported by thermal and nonthermal motion against gravity and the external pressure.

In some region, it was found that dissipation of turbulence in the molecular cloud core plays an essential role in star formation (e.g., Aso et al. 2000). However, it is known that molecular cloud cores in low-mass star forming regions are nearly thermally supported, and there is no ample room for turbulence dissipation. The main purpose of the present study is to make clear the role of turbulence dissipation in the archetypal low-mass star forming region, Taurus.

The secondary purpose is to make clear the effect of molecular depletion on studies of star formation. It becomes clear that carbon-bearing molecules popular for radio astronomy, CO, CS, and HCO^+ and their isotopomers are seriously affected by depletion via dust-related reaction, in cold (~ 10 K), starless molecular cloud cores (e.g. Bergin et al. 2002; Lee et al. 2003). Comparative studies between starless and star-forming cores may be affected by depletion, because depletion is effective in starless cores. It is important to know how observational results can be affected by depletion.

The distance to the Taurus molecular cloud is assumed to be 140 pc. At this distance, 1 arcmin corresponds to 0.041 pc.

II. OBSERVATION

We observed eight molecular cloud cores in Taurus in 2003 January. Four of them are starless (IRAS-less) cores, and the remaining four are star-forming cores. These targets were previously observed by Mizuno et al. (1994) in $H^{13}CO^+$. We used the 45-m radio telescope of Nobeyama Radio Observatory. The employed receiver front-end was a 25-element focal-plane receiver array, BEARS. The receiver back-end was a digital autocorrelator having 37.8 kHz (0.12 km s^{-1}) resolution. The half-power beam width (HPBW) at 93 GHz was 17.8 arcsec. Spectra were obtained on a 22.55 arcsec spacing grid. The position switching was employed. The telescope pointing was calibrated every 1-1.5 hr by observing the 43-GHz maser source NML Tau. The data were reduced by using the software package NewStar of Nobeyama Radio Observatory and IDL of Research Systems, Inc. The line intensity is reported here in terms of the corrected antenna temperature T_A^* obtained with the standard chopper wheel method.

III. RESULTS

Figure 1 shows the integrated intensity maps of the N_2H^+ emission toward eight Taurus molecular cloud cores. Crosses mark the locations of protostars. L1527 is associated with a Class 0 protostar, while Miz7 and L1551 are associated with Class I protostars.

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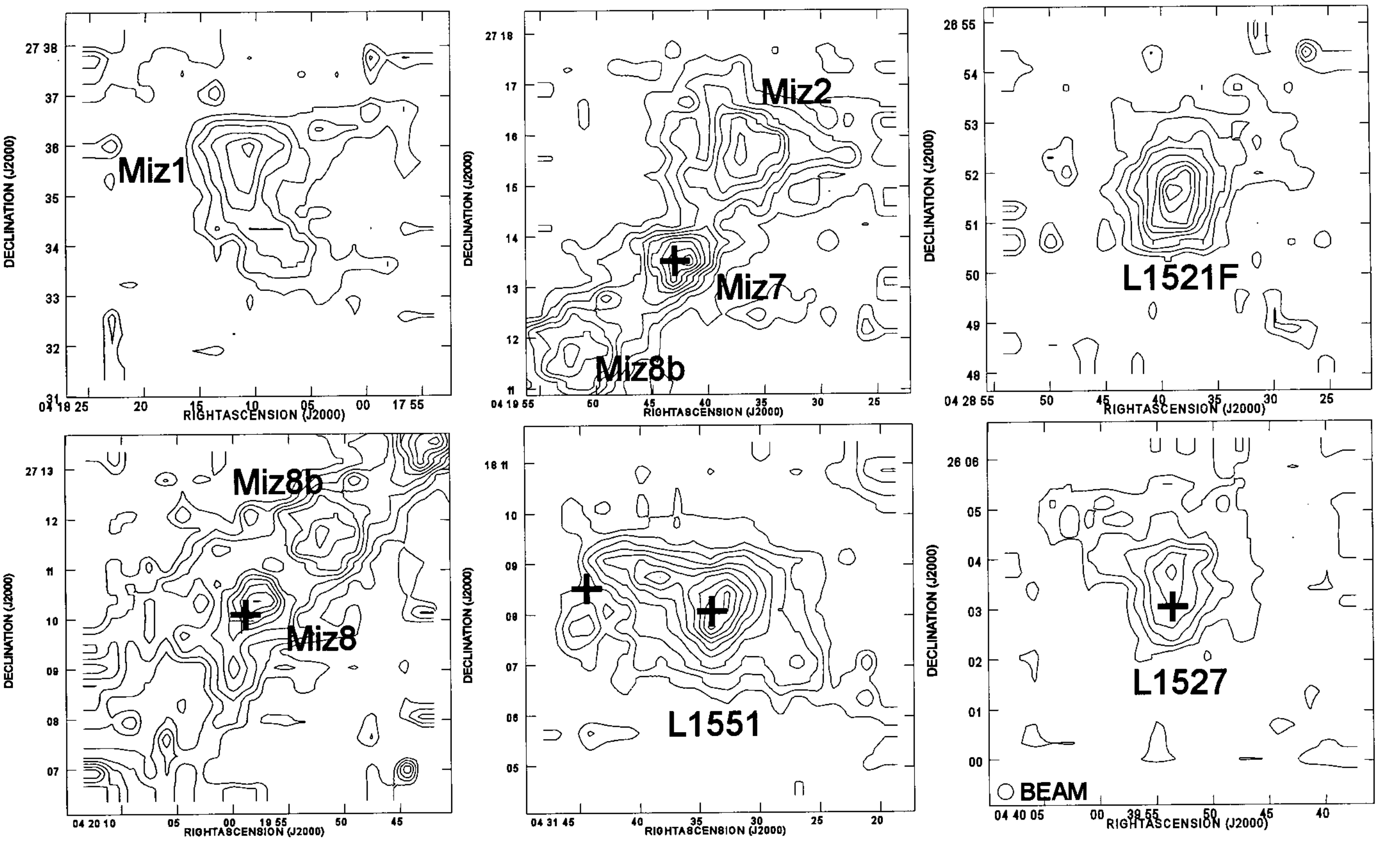

Fig. 1.— The velocity-integrated intensity map of the 93-GHz N_2H^+ emission (JF_1F = 1 2 3→0 1 2 main component) obtained with the Nobeyama 45-m radio telescope toward Taurus molecular cloud cores. The lowest contour level and interval are 0.1 K km s^{-1} for L1551. The lowest contour level and interval are 0.05 K km s^{-1} for the remaining cores. Crosses represent the positions of protostars.

The difference in the core appearance between starless and star-forming cores is not large. This is in sharp contrast with the result obtained by Mizuno et al. (1994), who claimed that starless cores are larger and less centrally-condensed. They suggested that the difference means core evolution/contraction toward star formation. However, it becomes clear that carbon-bearing molecules like $C^{18}O$, CS, and $H^{13}CO^+$ are easily depleted in cold starless cores. Because Mizuno et al. employed $H^{13}CO^+$, we are interested in how their results are affected by depletion. The reader are recommended to compare our Figure 1 with Figure 1 of Mizuno et al: these figures show the cores in the same order/arrangement. We conclude that the different results can be explained in terms of depletion of $H^{13}CO^+$ at the center of the starless core. Depletion will be efficient at the high-density core center, so the resulting map will show more flat-topped radial intensity distribution in depletion-affected lines. Then, starless cores tend to be weaker, and FWHM core size will become larger.

Because the N_2H^+ emission consists of seven hyperfine components, we have made hyperfine fitting by taking into account the optical depth effect. The optical depth of the most intense, main component (JF_1F = 1 2 3→0 1 2) is found to be moderate (1.54±0.78) for the intensity peak.

In star-forming cores, we found a tendency that the line width increases toward the center. We eliminate the core center, which is affected by the protostellar collapse and molecular outflow, from the average line width calculation in order to illustrate the intrinsic properties.

The observed properties are summarized as follows. The radius core is $R = 0.035\pm0.004$ and 0.031 ± 0.006 pc for starless and star-forming cores, respectively. Here, we define R to be the equivalent radius of the half-intensity contour, corrected for the telescope beam. The intrinsic line width is $\Delta v = 0.256\pm0.024$ and 0.309 ± 0.070 km s^{-1}, respectively. The line width is dominated by thermal motion, if we assume a kinetic temperature of 10 K. The core mass is 1.30±0.63

and 1.59±0.97 $M_\odot$, respectively, for starless and star-forming cores. The radial intensity profiles are shown in Figure 5 of Tatematsu et al. (2004). Cores with stars show shallow density profiles, $r^{-1.8}$ to $r^{-1.6}$.

IV. DISCUSSION

(a) Virial Analysis

We have analyzed the molecular cloud cores by using virial theorem including the external pressure. The procedure is explained in Nakano (1998). He introduced the critical pressure P_{cr}, which is a function of core mass M and sound speed (or line width). It can be expressed as $P_{cr} = 1/12\pi G^3 M^2 \times (5/3)^3 \times (9/4C_{eff}^2)^4$, where the effective sound speed C_{eff} includes nonthermal velocity component. When P_{cr} is higher than the actual external pressure, there are two equilibrium states: one is stable and the other is unstable. When P_{cr} is lower than the actual external pressure, there is no equilibrium state. Figure 2 plots P_{cr} against the core mass. Figure 2 includes the data of OMC-2/3 obtained by Aso et al. (2000). OMC-2/3 is one of the best studied intermediate-mass star-forming regions, where nonthermal motions are more prominent. In OMC-2/3, we see clear separation between starless and star-forming cores. Starless cores are stable, while star-forming cores are unstable. Aso et al. suggested that this separation means core evolution though the dissipation of turbulence, which reduces P_{cr}. On the other hand, there is no clear separation for Taurus cores. We conclude that both starless cores and star-forming cores are not far from the critical equilibrium state ($P_{cr} \sim P_s$).

As shown in Figure 3 of Nakano (1998), the critical equilibrium state in the virial theorem cloud correspond to the critical isothermal Bonnor-Ebert cloud.

(b) Related Work: Stability of Bok Globules

Kandori et al. (2004) studied the visual extinction distribution of Bok globules through near-infrared star count and color excess measurements. Note that their samples are not in Taurus but are located in the solar neighborhood (< 500 pc) along the Galactic plane (l = 0 to 50 degrees). They analyzed Bok globules by using Bonnor-Ebert analysis. Figure 3 shows the histogram of the logarithm of the center-to-edge density contrast. It is clear that the distribution of the starless cores is peaked near the critical Bonnor-Ebert sphere.

We should discuss how the detection limit of globules can affect the result of Figure 3. There is a possibility that the percentage of stable starless globules are small because of the selection effect: low density-contrast cores were missed in the observation. They derived an empirical relation between the peak A_V and the center-to edge density contrast. By using this relation, their detection limit A_V = 5 roughly corresponds to a density contrast of 4. Therefore, we believe that the (local) peak near the critical Bonnor-Ebert sphere in the histogram is real, although there is a possibility that very low density contrast globules are overlooked.

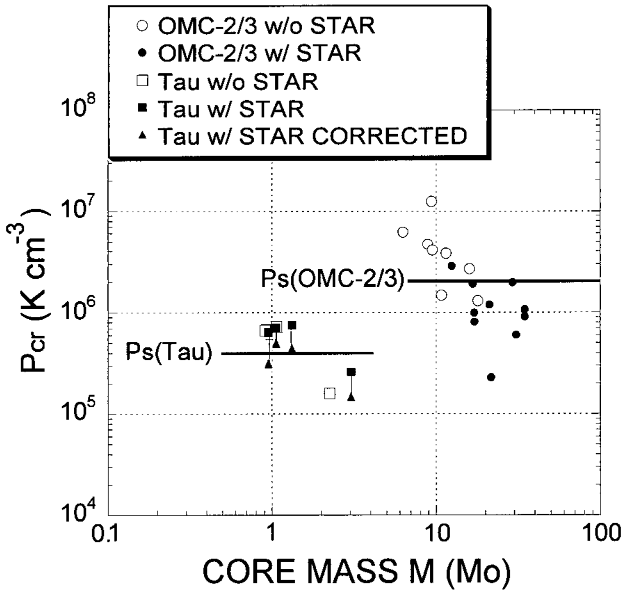

Fig. 2.— The critical pressure P_{cr} is plotted against the core mass. Circles represent cores in the intermediate-mass star forming region OMC-2/3 in Orion (Aso et al. 2000). Boxes and triangles represent the present work for Taurus cores. Triangles represent P_{cr} corrected for mass lost in the star formation process (protostellar accretion and outflow). The external pressure P_s is estimated from the linewidth-size relation and from the column density of low-density gas.

(c) Implications of the Critical Cores

It seems that the initial condition of Taurus cores and Bok globules is close to the critical Bonnor-Ebert, or the critical equilibrium state in the virial analysis. Nonthermal cores like those in OMC-2/3 can evolve toward star formation from stable equilibrium cores by dissipating turbulence. On the other hand, thermally supported cores like those in Taurus have much smaller room for dissipation of turbulence. How can they form stars?

If the thermal cores are very stable, it is hard for them to begin dynamical collapse toward star formation. They will have very long lifetime. On the other hand, if there are many near critical cores, they can begin dynamical collapse. Nakano (1998) suggested that only a slight loss of the magnetic flux via ambipolar diffusion at the core center will reduce P_{cr} efficiently even for magnetically supercritical cores.

Why are molecular cloud cores/globules in the low-mass star forming regions close to critical equilibrium state or critical Bonnor-Ebert sphere? It can be re-

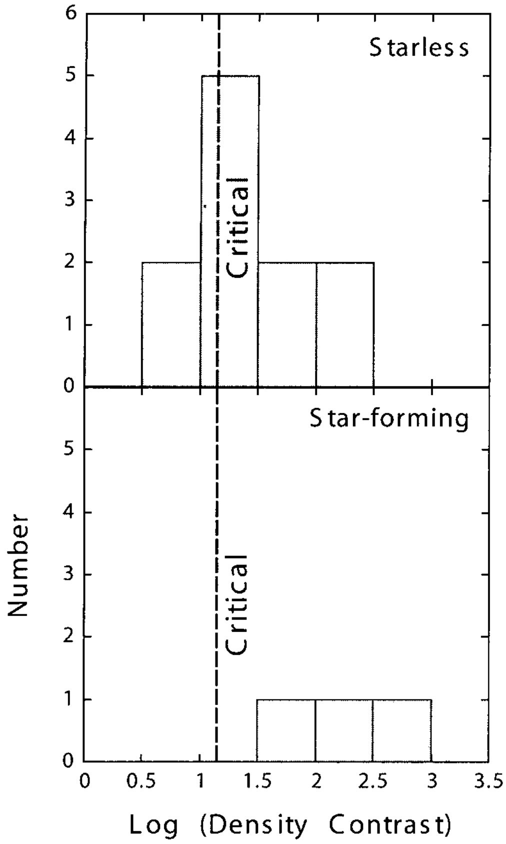

Fig. 3.— The histogram of the logarithm of the center-to-edge density contrast obtained for nearby globules by using near-infrared extinction data and Bonnor-Ebert analysis. When the density contrast is smaller than 14, cores/globules are stable. When the density contrast is larger than 14, cores/globules are unstable. Details will be given in Kandori et al. (2004).

lated to the formation/fragmentation process which form molecular cloud cores/globules. Further studies are needed for this topic.

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