ABSTRACT

$N_2H^+$ observations of molecular cloud cores in Taurus with the Nobeyama 45 m radio telescope are reported. We compare cores with young stars to cores without young stars. The differences in core radius, line width, and core mass are small. Line width is dominated by thermal motions in both cases. $N_2H^+$ maps show that the intensity distribution does not differ much between cores without stars and those with stars. This is in contrast to the result previously obtained in H$^{13}$CO$^+$ toward Taurus molecular cloud cores. A larger degree of depletion of H$^{13}$CO$^+$ in starless cores is one possible explanation for this difference. We studied the physical state of molecular cloud cores in terms of “critical pressure” for the surface (external) pressure. There is no systematic difference between starless cores and cores with stars in this analysis. Both are not far from the critical equilibrium state. We suggest that molecular cloud cores in which thermal support dominates evolve toward star formation by keeping close to the critical equilibrium state. This result is in contrast to that obtained in the intermediate-mass star-forming region OMC-2/3, where molecular cloud cores evolve by decreasing the critical pressure (dissipating turbulence). We investigate the radial distribution of the integrated intensity. Cores with stars are found to have shallow ($\sim 1.8$ to $1.6$) power-law density profiles.

Subject headings: ISM: clouds — ISM: individual (Taurus Cloud Complex) — ISM: molecules — ISM: structure — radio lines: ISM — stars: formation

1. INTRODUCTION

It is of great interest when and how the process of star formation takes place. Nakano (1998) studied the theory of the condition for the onset of star formation on the basis of the virial theorem. For the surface (external) pressure $P_s$, we can define the critical pressure $P_{cr}$, which is a function of the effective sound speed and the mass of the molecular cloud core (Spitzer 1968; Nakano 1998). There are two equilibrium states if $P_{cr} > P_s$, whereas there is no equilibrium state if $P_{cr} < P_s$. Nakano (1998) suggested that dissipation of turbulence in the core will result in the decrease in $P_{cr}$, which will lead to the onset of star formation because of the absence of an equilibrium state. Aso et al. (2000) observed the intermediate-mass star-forming region OMC-2/3 in Orion by using the H$^{13}$CO$^+$ $J = 1 \rightarrow 0$ line. They found that cores without young stars tend to have $P_{cr} > P_s$ and that cores with young stars tend to have $P_{cr} < P_s$. This fact suggests that dissipation of turbulence leads to the onset of star formation in OMC-2/3.

It seems that molecular cloud cores in low-mass star-forming regions like Taurus have lower surface (external) pressure than those in massive or intermediate-mass star-forming regions like Orion (Tatematsu et al. 1993). The present study aims to investigate whether dissipation of turbulence plays an important role also in low-mass star-forming regions. In low-mass star-forming regions, the choice of the molecular line tracers is crucial. It is known that molecular depletion seems to be serious for CO, HCO$^+$, CCS, CS, and their isotopomers in starless, cold molecular cloud cores (Caselli et al. 1999; Aikawa et al. 2001; Bergin et al. 2001, 2002; Li et al. 2002; Tafalla et al. 2002; Lee et al. 2003; Shematovich et al. 2003). On the other hand, N-bearing molecules, NH$_3$ and N$_2$H$^+$, do not show strong evidence of depletion except at the very center of the cores (Bergin et al. 2001, 2002; Caselli et al. 2002c; Tafalla et al. 2002; Lee et al. 2003; Shinnaga et al. 2004). Furthermore, although H$^{13}$CO$^+$ is one of the popular tracers of the molecular cloud core, it is known that the line width of the H$^{13}$CO$^+$ core can be broadened by the molecular outflow; this is more serious in studying low-mass star-forming regions (Aso et al. 2000). We employ N$_2$H$^+$, which is less affected by depletion or molecular outflow. N$_2$H$^+$ is found to trace the quiescent molecular gas (Womack, Ziurys, & Sage 1993; Bachiller & Perez Gutierrez 1997), and this choice would minimize the influence of the molecular outflow.

The target molecular cloud cores are those observed by Mizuno et al. (1994) in H$^{13}$CO$^+$. Molecular cloud cores associated with young stars are called “cores with stars.” Molecular cloud cores not associated with young stars are called “starless cores.” Our samples contain three starless cores and four cores with stars. We happened to detect one new starless core during the observations. The distances to cores in Taurus are assumed to be 140 pc. At this distance, $1^\circ$ corresponds to 0.041 pc.

2. OBSERVATIONS

We carried out our observations by using the 45 m radio telescope of Nobeyama Radio Observatory from 2003 January 7 to 9. The receiver front end was the 25 element, double-sideband, focal-plane SIS receiver BEARS, which has a beam separation of 41$^\prime$.1. We observed molecular cloud cores in N$_2$H$^+ J = 1 \rightarrow 0$ at 93.1737767 GHz (Caselli, Myers, & Thaddeus 1995). We mapped regions by shifting the telescope by half the beam separation, so the final map consists of data on a 20$^\prime$.55 spacing grid. During the observations, one element of BEARS was not available because of a technical problem,
so we used 24 elements. The half-power beamwidth of the element beams of BEARS was estimated to be $17''8 \pm 0'4$ at 93 GHz, which was close to the data grid spacing. The receiver back end employed was a digital autocorrelator. We selected the spectral resolution to be 37.8 kHz (corresponding to $\sim 0.12$ km s$^{-1}$). Spectra were obtained in the position-switching mode. To compensate for the daily intensity-scale variation, we observed a local intensity peak at R.A. (J2000) = 5$^h$35$^m$16$^s$, decl. (J2000) = $-5^\circ19'26''$ near Orion KL with BEARS every day. Furthermore, we observed this intensity peak using a single-sideband SIS receiver S100 to calibrate the gain of each BEARS element and to establish the absolute intensity scale. The line intensity is reported in terms of the corrected antenna temperature $T_A^*$. The main beam efficiency with S100 at 93 GHz is estimated to be 0.515 by interpolating the measurements at 86 and 100 GHz by the observatory. The telescope pointing was established by observing the SiO maser source NML Tau at 43 GHz every 1–1.5 hr during the observations. The data were reduced by using the software package NewStar of Nobeyama Radio Observatory and IDL of Research Systems, Inc.

Prior to our observations, 63 low-mass molecular cloud cores were observed in N$_2$H$^+$ by Caselli et al. (2002a), but with lower angular resolution (54'). We refer to their results to secure our discussion on the basis of our observations toward the eight cores but with better angular resolution (18'6 beam and 20'55 grid). Since the typical radius of the molecular cloud core is about 50'' in the region, the improvement in spatial resolution helps us to derive the physical parameters more precisely.

3. RESULTS

Figure 1 shows the distribution of the velocity-integrated intensity of the main N$_2$H$^+$ ($J = 1 2 3 \rightarrow 0 1 2$) component toward the eight molecular cloud cores. Core L1551 is 2–3 times as intense as the other cores, and we double the contour interval for this source for clarity. We use the main component rather than the optically thinner components to obtain better signal-to-noise ratios. For checking, we have also made integrated intensity maps of the $J = 1 0 1 \rightarrow 0 1 2$ component (not shown, as the map quality is much worse) and have confirmed that the intensity peak position is consistent in general. As shown later, the optical depth is not very large even for the main component (~unity). The positions of the intensity maxima of the cores are summarized in Table 1. The core name with the prefix of Miz refers to the core number in Mizuno et al. (1994).

Core Miz8b was recently found in our observations. Core L1527 is associated with a Class 0 protostar, while cores Miz7, Miz8, and L1551 are associated with Class I protostars. These are cores with stars. Furthermore, a Class 0 protostar L1551 NE (Barsony & Chandler 1993) is located near the core boundary of L1551, but its relationship to the N$_2$H$^+$ core is not clear in our map (see Saito et al. 2001; Yokogawa et al. 2003 for a detailed study of this region in C$^{18}$O and CS). Cores Miz1, Miz2, L1521F, and Miz8b are starless cores.

The basic physical parameters of the cores are summarized in Table 2. The half-width at half-maximum (HWHM) core radius $R$ is measured as $\sqrt{S/\pi}$ ($S$ is the core area at the half-maximum) and then corrected for the telescope beam size. There is no remarkable difference in core radius between starless cores ($R = 0.353 \pm 0.004$ pc) and cores with stars ($R = 0.326 \pm 0.006$ pc). The study of Caselli et al. (2002a) shows that cores with stars are slightly larger than starless cores, but the difference is not large. Our result is in marked contrast to that of Mizuno et al. (1994) in H$^{13}$CO$^+$, in which cores with stars tend to be more compact. Depletion of H$^{13}$CO$^+$ is a plausible explanation, because it is known that N$_2$H$^+$ is more robust against depletion than H$^{13}$CO$^+$ (Bergin et al. 2001; Caselli et al. 2002c; Lee et al. 2003). It is suggested that depletion becomes less prominent in cores with high density.
stars because molecules evaporate from the dust grain through radiation and outflow from the newly formed star (Langer et al. 2000). If some molecule is depleted in starless cores, we expect that intensity tends to be weak in starless cores, and the radial intensity profile is more flat-topped (because depletion is more effective at the high-density core center), causing a larger radius in starless cores. The tendency observed in $^{13}$CO can be explained if this molecule is depleted substantially only in starless cores.

Next, we derive the line optical depth, line width, and mass. We fit the observed spectrum by using the hyperfine spectrum model consisting of multiple Gaussian components with line optical depth effect. The intrinsic relative intensities of the hyperfine components are taken from Tiné et al. (2000). The free parameters are the excitation temperature $T_{\text{ex}}$, the sum of optical depths of the hyperfine components $\tau_{\text{tot}}$, systemic velocity (radial velocity), and intrinsic line width (which is not broadened because of line optical depth). The details of the column density estimation are given in Caselli et al. (2002c). We used the optically thick formula for the central 3 × 3 positions and the optically thin formula for the weaker, outer part. Figure 2 shows the results of the hyperfine fitting, and Table 2 lists the physical parameters from the hyperfine fitting. The excitation temperature at the intensity peak is $T_{\text{ex}} = 6.2 \pm 2.3$ K for the seven cores excluding Miz1. That of the composite spectrum from the central nine (3 × 3) positions is $T_{\text{ex}} = 5.7 \pm 1.2$ K for the eight cores. The optical depth of the main N$_2$H$^+$ ($J = 1 \rightarrow 0$) component, which is equal to 0.259$\tau_{\text{tot}}$, is found to be moderate (1.54 ± 0.78 for the intensity peak and 1.07 ± 0.65 for the central nine positions). The derived line width is then corrected for the frequency resolution of the spectrometer. Figure 3 plots the intrinsic line width against the angular distance from the core center (impact parameter) $b$. This corresponds to the type 4 (single tracer, single cloud) line width–size relation in Goodman et al. (1998). The power-law index of the line width–size relation obtained by nonlinear least-squares fitting is listed in Table 3. Caselli et al. (2002a) showed that molecular cloud cores have a variety of line width–size relations; cores show positive, flat, and negative correlation of line width with the impact parameter. Our samples show that line width decreases or remains constant with increasing $b$ in general (Table 2). The larger line width at the center in cores with stars could be due to the influence of protostellar collapse (Zhou et al. 1994; Caselli et al. 2002b) and/or molecular outflow (Asó et al. 2000), although we selected the molecular line to minimize such effects. To discuss the intrinsic core properties by eliminating this effect, we use the average line width for $b > 40''$ in Miz8 and L1527 and for $b > 80''$ in L1551. The intrinsic N$_2$H$^+$ line width of the starless core is $\Delta v = 0.256 \pm 0.024$ km s$^{-1}$, while that of the core with stars is $\Delta v = 0.309 \pm 0.070$ km s$^{-1}$. Therefore, there is no significant difference. By assuming a gas kinetic temperature of 10 K, we derive the nonthermal line width $\Delta v_{\text{NT}}$ and the total line width $\Delta v_{\text{tot}}$ (Fulcher & Myers 1992). The $\Delta v_{\text{NT}}$ is estimated to be $0.224 \pm 0.030$ and $0.284 \pm 0.082$ km s$^{-1}$ for starless cores.

### TABLE 1
**Observed Molecular Cloud Cores**

| Field     | R.A. (J2000)$^a$ | Decl. (J2000)$^a$ | Parent Cloud Name | IRAS / Young Star Class |
|-----------|-----------------|-----------------|------------------|-------------------------|
| Miz1      | 04 18 10.3      | 27 36 03        | L1495            |                        |
| Miz2      | 04 19 37.0      | 27 15 35        | L1495            |                        |
| L1521F    | 04 28 39.3      | 26 51 43        | L1521            |                        |
| Miz7      | 04 19 41.5      | 27 13 32        | L1495            | 04166+2706             |
| Miz8      | 04 19 58.2      | 27 10 22        | L1495            | 04169+2702             |
| Miz8b     | 04 19 52.2      | 27 11 45        | L1495            |                        |
| L1551     | 04 31 32.5      | 18 08 25        | L1551            | L1551 IRS 5            |
| L1527     | 04 39 53.2      | 26 03 47        | L1527            | 04368+2557             |

$^a$ The maximum position of the main N$_2$H$^+$ ($J = 1 \rightarrow 0$) component is listed. Units of right ascension are hours, minutes, and seconds, and units of declination are degrees, arcminutes, and arcseconds.

### TABLE 2
**Radius, Velocity, Line Width, Optical Depth, and Excitation Temperature**

| CORE      | R (pc) | $V_{\text{LSR}}$ (km s$^{-1}$) | $\Delta v$ (km s$^{-1}$) | $\tau_{\text{ex}}$ | $T_{\text{ex}}$ (K) |
|-----------|--------|-------------------------------|--------------------------|---------------------|---------------------|
|           | Peak$^a$ | Composite$^b$ | Peak$^a$ | Composite$^b$ | Peak$^a$ | Composite$^b$ | Peak$^a$ | Composite$^b$ |
| Miz1      | 0.038  | 6.75 ± 0.01                  | 6.76 ± 0.01              | 0.28 ± 0.04         | 2.81 ± 1.07         | 4.86 ± 0.62         |
| Miz2      | 0.036  | 6.83 ± 0.01                  | 6.84 ± 0.01              | 0.24 ± 0.05         | 4.00 ± 1.33         | 2.73 ± 0.86         | 6.23 ± 0.83         | 5.99 ± 0.80         |
| L1521F    | 0.029  | 6.50 ± 0.01                  | 6.51 ± 0.01              | 0.28 ± 0.04         | 9.72 ± 1.79         | 9.63 ± 0.87         | 5.07 ± 0.23         | 4.65 ± 0.09         |
| Miz7      | 0.024  | 6.72 ± 0.01                  | 6.70 ± 0.01              | 0.24 ± 0.05         | 7.64 ± 1.33         | 5.03 ± 0.72         | 5.78 ± 0.31         | 5.47 ± 0.26         |
| Miz8      | 0.029  | 6.75 ± 0.01                  | 6.77 ± 0.01              | 0.33 ± 0.05         | 7.92 ± 1.78         | 4.54 ± 1.06         | 5.02 ± 0.29         | 4.78 ± 0.33         |
| Miz8b     | 0.036  | 6.73 ± 0.01                  | 6.71 ± 0.01              | 0.23 ± 0.06         | 3.96 ± 1.79         | 1.89 ± 0.82         | 5.91 ± 1.03         | 7.40 ± 1.67         |
| L1551     | 0.038  | 6.41 ± 0.02                  | 6.43 ± 0.01              | 0.40 ± 0.10         | 1.06 ± 0.79         | 2.19 ± 0.42         | 11.20 ± 5.53        | 7.60 ± 0.73         |
| L1527     | 0.032  | 5.85 ± 0.01                  | 5.88 ± 0.01              | 0.27 ± 0.07         | 7.43 ± 1.94         | 4.21 ± 0.88         | 4.20 ± 0.22         | 4.60 ± 0.28         |

$^a$ Value at the intensity peak. The error represents 1 $\sigma$ error in the hyperfine fitting.

$^b$ Value from the composite spectrum of the central nine positions. The error represents 1 $\sigma$ error in the hyperfine fitting.

$^c$ Intrinsic N$_2$H$^+$ line width. For Miz8, L1551, and L1527, the values derived for the core edge ($b > 40''$, 80'', and 40'', respectively) are used to minimize the effect of the protostellar collapse and molecular outflow. For the remaining sources, the average values over the cores are used.

$^d$ Very large uncertainty.
and cores with stars, respectively, and $\Delta v_{\text{tot}}$ is derived to be $0.497 \pm 0.013$ and $0.528 \pm 0.042$ km s$^{-1}$ for starless cores and cores with stars, respectively. The thermal line width $\Delta v_T$ for the mean molecular weight ($2.33 m_H$) at 10 K is 0.443 km s$^{-1}$. Therefore, both starless cores and cores with stars are dominated by thermal support.

The effective pressure is $1.26 \pm 0.07$ and $1.43 \pm 0.23$ times as large as the thermal pressure for starless cores and cores with stars, respectively. Table 3 lists the H$_2$ column density $N$(H$_2$) obtained for the spectrum at the intensity peak and for the composite spectrum from the nine ($3 \times 3$) positions centered on the intensity peak. We derive the core mass $M$ by integrating the column density over the core. We adopted the abundance of N$_2$H$^+$ to be $3.0 \times 10^{-10}$ relative to H$_2$ (Caselli et al. 2002a). The core mass $M$ is listed in Table 3. The average value is $M = 1.30 \pm 0.63 M_\odot$ for the starless cores and $1.59 \pm 0.97 M_\odot$ for the cores with stars. These values are not much different, taking into account the uncertainty in mass estimation (a factor of 2).

4. DISCUSSION

We investigate whether the cores have equilibrium states or not by following the discussion of Nakano (1998) (see § 1 for a brief summary). The virial theorem is useful not only for stable states but also for the unstable states not very far from the critical state (Nakano 1998). For consistency, the formula in Aso et al. (2000) is used again,

$$P_{\text{cr}} = \frac{1}{12 \pi G^3 M^2} \left( \frac{5}{3} \right) \left( \frac{9}{4} C_{\text{eff}}^2 \right)^4,$$

where the effective sound speed $C_{\text{eff}}$ is $C_{\text{eff}} = (\Delta v_{\text{tot}}^2/8 \ln 2)^{1/2}$. Table 3 lists the critical pressure $P_{\text{cr}}$, which is derived to be $(5.4 \pm 2.6) \times 10^5$ and $(5.9 \pm 2.2) \times 10^5$ K cm$^{-3}$ for starless cores.

Fig. 2.—Composite N$_2$H$^+$ spectra made by using the central nine positions. The result of the hyperfine fitting is also shown.
cores and cores with stars, respectively, when we do not correct for the decrease in mass (see below). When we correct for the decrease in mass due to protostellar collapse and outflow for cores with stars, the critical pressure $P_{\text{cr}}$ is derived to be $\left(5.4 \pm 2.6\right) \times 10^5$ and $\left(3.5 \pm 1.6\right) \times 10^5$ K cm$^{-3}$ for starless cores and cores with stars, respectively. We estimate $P_s$ in Taurus to be of the order of $4 \times 10^5$ K cm$^{-3}$ from the column density of low-density molecular gas and the coefficient of the line width–size relation (Tatematsu et al. 1993; Onishi et al. 2002). This means that both starless cores and cores with stars are below the critical pressure for gravitational collapse.

TABLE 3

| Core   | $N(H_2)$ (cm$^{-3}$) | $M^c$ (M$_\odot$) | $P_{\text{cr}, d}^d$ (10$^5$ K cm$^{-3}$) | Power-Law Index of Line Width–Size Relation$^e$ | Correlation Coefficient | Power-Law Index of Intensity Distribution$^f$ |
|--------|----------------------|------------------|-------------------------------------------|---------------------------------|------------------------|---------------------------------|
| Miz1... | $8$                  | $1.0 \pm 0.4 \times 10^{22}$ | $7.3$ | $-0.23 \pm 0.18$ | $0.88$ | $-1.2 \pm 0.3^b$ |
| Miz2... | $1.3 \pm 0.5 \times 10^{22}$ | $1.1 \pm 0.4 \times 10^{22}$ | $7.3$ | $-0.42 \pm 0.14$ | $0.79$ | $-1.1 \pm 0.2^b$ |
| L1521F.. | $3.0 \pm 0.6 \times 10^{22}$ | $2.8 \pm 0.3 \times 10^{22}$ | $7.3$ | $-0.17 \pm 0.08$ | $0.48$ | $-1.0 \pm 0.2$ |
| Miz7... | $2.2 \pm 0.4 \times 10^{22}$ | $2.2 \pm 0.1 \times 10^{22}$ | $7.3$ | $-0.02 \pm 0.34$ | $0.98$ | $-0.7 \pm 0.2$ |
| Miz8... | $2.6 \pm 0.6 \times 10^{22}$ | $2.6 \pm 0.4 \times 10^{22}$ | $7.3$ | $-0.41 \pm 0.36$ | $0.92$ | $-0.6 \pm 0.1$ |
| Miz8b... | $1.3 \pm 0.6 \times 10^{22}$ | $0.9 \pm 0.4 \times 10^{22}$ | $7.3$ | $-0.14 \pm 0.25$ | $0.68$ | $-0.8 \pm 0.1$ |
| L1551.... | $2.2 \pm 0.7 \times 10^{22}$ | $3.0 \pm 0.6 \times 10^{22}$ | $7.3$ | $-0.31 \pm 0.13$ | $0.97$ | $-0.8 \pm 0.1$ |
| L1527.... | $2.2 \pm 0.6 \times 10^{22}$ | $1.4 \pm 0.3 \times 10^{22}$ | $7.3$ | $-0.23 \pm 0.19$ | $0.79$ | $-0.7 \pm 0.1$ |

$^a$ Value at the intensity peak. The error represents 1 $\sigma$ error in the hyperfine fitting.

$^b$ Value from the composite spectrum of the central nine positions. The error represents 1 $\sigma$ error in the hyperfine fitting.

$^c$ Mass lost to the forming star and the associated molecular outflow is not taken into account.

$^d$ For cores with stars, the “range” represents the values uncorrected (upper bound) and as corrected (lower bound) for the mass loss due to accretion onto the star and due to the molecular outflow.

$^e$ Power-law index $q$ for the line width–size relation (Fig. 3) estimated by using the nonlinear least-squares fitting in the form $\Delta v \propto b^q$.

$^f$ Power-law index from the fit to the radial integrated intensity distribution of the main component (Fig. 5).

$^g$ Very large uncertainty.

$^h$ Central part is excluded for fitting.
cores with stars are close to the critical state $P_{cr} \sim P_s$ in Taurus.

To know whether turbulence dissipation leads to the onset of star formation, we need to know the physical condition prior to star formation. The derived mass of the molecular cloud core is the current value. This may have decreased from the original value, because part of the original core mass has been lost through star formation. We estimate the decrease in the core mass due to these star formation activities as follows. Part of the core mass will be accreted onto the protostar, and part of it will be swept up by the molecular outflow. The high-velocity wind from the protostar will sweep up the ambient matter (mostly the parent molecular cloud core, and possibly also the less dense envelope), and this entrained mass together with the wind mass constitutes the outflow mass. The mass of the T Tauri star is typically $0.5 M_\odot$. The Class I protostar is supposed to have accreted more than half of the final stellar mass (Bontemps et al. 1996). The mass of the forming star is estimated to be $0.1-0.15 M_\odot$ for IRAS 04169+2702 from the accretion luminosity estimate (Ohashi et al. 1997b). The mass of the central star of L1551 IRS 5 is estimated to be $0.15-0.5 M_\odot$ from the kinematics of the protoplanetary disk (Momose et al. 1998) and to be $0.7-3 M_\odot$ from the stellar luminosity and disk mass (Saito et al. 1996). The mass of the central star of IRAS 04368+2557 (L1527) is estimated to be $0.1 M_\odot$ from the kinematics of the protoplanetary disk and the accretion luminosity (Ohishi et al. 1999). Hogerheijde et al. (1998) estimated the maximum central star mass to be 2.6 and $0.2 M_\odot$ for L1551 IRS 5 and IRAS 04368+2557 (L1527), respectively, from the accretion luminosity. IRAS 04166+2706 (Miz7), IRAS 04169+2702 (Miz8), and IRAS 04368+2557 (L1527) are known to accompany molecular outflows (Bontemps et al. 1996). The mass of molecular outflow associated with L1551 IRS 5 is $0.3 M_\odot$ (Lada 1985). Hogerheijde et al. (1998) estimated the outflow mass from $^{13}$CO $(3 \rightarrow 2)$ to be $3.1$ and $0.18 M_\odot$ for L1551 IRS 5 and IRAS 04368+2557 (L1527), respectively. Taking them into account, we estimate that the mass lost from the parent molecular cloud core is about $0.4, 0.4, 1.0$, and $0.2 M_\odot$ for IRAS 04166+2706 (Miz7), IRAS 04169+2702 (Miz8), L1551 IRS 5, and IRAS 04368+2557 (L1527), respectively.

Figure 4 plots the critical pressure $P_{cr}$ against the core mass $M$. There is no systematic difference between starless cores and cores with stars in Taurus. Whether or not cores are associated with stars, six out of the eight molecular cloud cores are located near the critical state of equilibrium. Two cores, L1521F$^2$ and L1551, are located slightly below $P_s$. However, $P_s$ may have local variation, and the mass estimation is uncertain by a factor of 2. It is hard to conclude that these two cores are far from the critical state. Although there is a possibility that the core in Taurus slightly dissipates turbulence resulting in star formation and then the star formation activity increases the nonthermal line width, the present observations do not provide us with evidence for the dissociation of turbulence. Within the accuracy of the current study, we conclude that both starless cores and cores with stars are close to the critical state. Note that the critical equilibrium state $P_{cr} = P_s$ corresponds to the separation between stable and unstable states (Nakano 1998). Myers & Benson (1983) obtained similar results from NH$_3$ observations of low-mass molecular cloud cores; cores are close to the critical state for equilibrium.

---

2 Onishi et al. (1999) and Lee et al. (1999) obtained a hint of infall motions in the starless core L1521F.

---

**Fig. 4.—** Critical pressure $P_{cr}$ plotted against the core mass $M$. For Taurus cores with stars, $P_{cr}$ corrected for mass lost through accretion onto the protostar and the outflow is also shown as filled triangles. For reference, OMC-2/3 cores (Aso et al. 2000) are also plotted. The horizontal lines at $4 \times 10^5$ and $2 \times 10^6$ K cm$^{-3}$ represent the estimated core surface (external) pressure $P_s$ for Taurus cores and OMC-2/3 cores, respectively.

---

and stability if the Doppler line width supports cores. Caselli et al. (2002a) studied the ratio of the core mass to the virial mass and derived it to be $1.3 \pm 0.3$ and $1.4 \pm 0.3$ for starless cores and cores with stars, respectively. These values are almost identical: both cores are close to virial equilibrium. We suggest that the thermally supported cores evolve keeping close to the critical equilibrium state. This result for the low-mass star-forming region is in contrast to that obtained in the intermediate-mass star-forming region OMC-2/3. In OMC-2/3, starless cores and cores with stars show clearly different states.

We should revisit OMC-2/3 to see whether the results reported are still correct even if we take into account the depletion of H$^{13}$CO$^+$. The molecular cloud cores in OMC-2/3 are warmer ($\sim 20$ K; Cesaroni & Wilson 1994) and show active star formation. The sublimation temperature of the CO ice is $16$ K in cloud cores (Langer et al. 2000). So, depletion will not be serious even for H$^{13}$CO$^+$. Aso et al. (2000) have not taken into account the mass accreted onto the protostar or swept by the outflow, but this correction will simply enhance the observed difference between starless cores and cores with stars. We conclude that the results obtained by Aso et al. (2000) are unchanged even in the present context.

Finally, we investigate the radial density profile on the basis of the radial distribution of the integrated intensity of the main component (Fig. 5). We use here the integrated intensity because it is straightforward and more reliable than the hyperfine fitted column density for outer regions. The intensity profile is fitted with a power-law $I \propto \rho^p$ convolved with the telescope beam. The fitting results are listed in Table 3. Miz1 and Miz2 may have (a hint of) central flattening. For Miz1 and Miz2, the fitting result only for the outer part ($\geq 35''$) or $>4800$ AU) is shown as dashed lines in Figure 5. The central flattening in cores in low-mass star-forming regions was previously reported by Ward-Thompson, Motte, & André (1999), André, Ward-Thompson, & Barsony (2000), and Caselli et al. (2002a)
from the dust continuum observations and N$_2$H$^+$ observations. However, the integrated intensity profile in Miz1 and Miz2 can also be fitted reasonably with single (shallow) power laws (solid lines). The data quality of the present observation is not enough to distinguish these models. The power-law index of the radial distribution is $p = 1.00 \pm 0.14$ (using the outer part for Miz1 and Miz2) and $-0.72 \pm 0.07$ for starless cores and cores with stars, respectively. When we assume that the column density is proportional to the integrated intensity, the power $p$ in the intensity profile is related to the power $\alpha$ in the density profile $\rho \propto r^\alpha$ as $\alpha = p - 1$. L1521F was observed in N$_2$H$^+$ with the Berkeley-Illinois-Maryland Association (BIMA) millimeter array and with SCUBA on the James Clerk Maxwell Telescope (JCMT) (Shinnaga et al. 2004). These observations show the centrally peaked intensity profile of L1521F (from their Figure 3, the BIMA intensity profile is fitted with $p \sim -1.3$ and the SCUBA intensity profile is fitted with $p \sim -1.0$ for $r > 10'$). These data do not show the central flattening for L1521F when we take into account their map resolution. Some starless cores (Miz1 and Miz2) may have central flattening, while other starless cores may not. On the other hand, there is no hint of central flattening in cores with stars in our samples. However, it is possible that central flattening was not observed because of the limited spatial resolution ($\sim 18''$ or 2500 AU) and data sampling ($\sim 21''$ or 2900 AU) in our observations. Our result shows that cores with stars have shallow power-law density (or integrated intensity) distribution. It is interesting that this is in contrast to the result in the lower spatial resolution study by Caselli et al. (2002a), where cores with stars show steep integrated intensity distribution. There is a possibility that the shallow density profile in cores with stars can be the result of the collapse (e.g., Foster & Chevalier 1993) and/or core dispersal due to the molecular outflow. The present observations are probably not sufficient to disentangle these possibilities, and further observations (high-resolution dust continuum map, near-infrared color excess map, higher resolution N$_2$H$^+$ imaging, etc.) are desirable.

5. SUMMARY

On the basis of N$_2$H$^+$ observations toward Taurus, we have studied the physical properties of the molecular cloud core. The core radius, line width, and intensity distribution do not differ much between starless cores and cores with stars. This result is in contrast with that previously obtained in H$^{13}$CO$^+$. We suggest that depletion of H$^{13}$CO$^+$ causes this difference. From the critical pressure analysis for Taurus cores, there is no systematic difference between starless cores and cores with stars. Both are not far from the critical equilibrium state. We suggest that the Taurus starless cores, which are almost thermally supported, evolve toward star formation by keeping close to the critical equilibrium state. This result is in contrast to that obtained in the intermediate-mass star-forming region OMC-2/3, where the molecular cloud core evolves by dissipating turbulence. The density profile is investigated from the integrated intensity distribution in the cores. Cores with stars show shallow density profiles, $p^{-1.8}$ to $p^{-1.6}$.

K. T. is grateful to Takenori Nakano for comments on the draft and to Jeong-Eun Lee for discussion.
REFERENCES

Aikawa, Y., Ohashi, N., Inutsuka, S., Herbst, E., & Takakuwa, S. 2001, ApJ, 552, 639

André, P., Ward-Thompson, D., & Barsony, M. 2000, in Protostars and Planets IV, ed. V. Mannings, A. P. Boss, & S. S. Russell (Tucson: Univ. Arizona Press), 59

Aso, Y., Tatamatsu, K., Sekimoto, Y., Nakano, T., Umemoto, T., Koyama, K., & Yamamoto, S. 2000, ApJS, 131, 465

Bachiller, R., & Perez Gutierrez, M. 1997, ApJ, 487, L93

Barsony, M., & Chandler, C. J. 1993, ApJ, 406, L71

Bergin, E. A., Alves, J., Huard, T. L., & Tafalla, M. 2002, ApJ, 570, L101

Bergin, E. A., Ciardi, D. R., Lada, C. J., Alves, J., & Lada, E. A. 2001, ApJ, 557, 209

Bontemps, S., André, P., Terebey, S., & Cabrit, S. 1996, A&A, 311, 858

Caselli, P., Benson, P. J., Myers, P. C., & Tafalla, M. 2002a, ApJ, 572, 238

Caselli, P., Myers, P. C., & Thaddeus, P. 1995, ApJ, 455, L77

Caselli, P., Walmsley, C. M., Tafalla, M., Dore, L., & Myers, P. C. 1999, ApJ, 523, L165

Caselli, P., Walmsley, C. M., Zucconi, A., Tafalla, M., Dore, L., & Myers, P. C. 2002b, ApJ, 565, 331

Cesaroni, R., & Wilson, T. L. 1994, A&A, 281, 209

Foster, P. N., & Chevalier, R. A. 1993, ApJ, 416, 303

Fuller, G. A., & Myers, P. C. 1992, ApJ, 384, 523

Hogerheijde, M. R., van Dishoeck, E. F., Blake, G. A., & van Langevelde, H. J. 1998, ApJ, 502, 315

Goodman, A. A., Barranco, J. A., Wilner, D. J., & Heyer, M. H. 1998, ApJ, 504, 223

Lada, C. J. 1985, ARA&A, 23, 267

Langer, W. D., van Dishoeck, E. F., Bergin, E. A., Blake, G. A., Tielens, A. G. G. M., Velsusamy, T., & Whittet, D. C. B. 2000, in Protostars and Planets IV, ed. V. Mannings, A. P. Boss, & S. S. Russell (Tucson: Univ. Arizona Press), 29

Lee, C. W., Myers, P. C., & Tafalla, M. 1999, ApJ, 526, 788

Lee, J.-E., Evans, N. J., II, Shirley, Y. L., & Tatamatsu, K. 2003, ApJ, 583, 789

Li, Z.-Y., Shematovich, V. I., Wiebe, D. S., & Shustov, B. M. 2002, ApJ, 569, 792

Mizuno, A., Onishi, T., Hayashi, M., Ohashi, N., Sunada, K., Hasegawa, T., & Fukui, Y. 1994, Nature, 368, 719

Momose, M., Ohashi, N., Kawabe, R., Nakano, T., & Hayashi, M. 1998, ApJ, 504, 314

Myers, P. C., & Benson, P. J. 1983, ApJ, 266, 309

Nakano, T. 1998, ApJ, 494, 587

Ohashi, N., Hayashi, M., Ho, P. T. P., & Momose, M. 1997a, ApJ, 475, 211

Ohashi, N., Hayashi, M., Ho, P. T. P., Momose, M., Tamura, M., Hirano, N., & Sargent, A. I. 1997b, ApJ, 488, 317

Onishi, T., Mizuno, A., & Fukui, Y. 1999, PASJ, 51, 257

Onishi, T., Mizuno, A., Kawamura, A., Tachihara, K., & Fukui, Y. 2002, ApJ, 575, 950

Saito, M., Kawabe, R., Kitamura, Y., & Sunada, K. 1996, ApJ, 464, 464

———. 2001, ApJ, 547, 840

Shematovich, V. I., Wiebe, D. S., Shustov, B. M., & Li, Z.-Y. 2003, ApJ, 588, 894

Shinnaga, H., Ohashi, N., Lee, S.-W., & Moriarty-Schieven, G. H. 2004, ApJ, 601, 962

Spitzer, L., Jr. 1968, Di\use Matter in Space (New York: Wiley)

Tafalla, M., Myers, P. C., Caselli, P., Walmsley, C. M., & Comito, C. 2002, ApJ, 569, 815

Tatematsu, K., et al. 1993, ApJ, 404, 643

Tódé, S., Roueff, E., Falgarone, E., Gerin, M., & Pineau des Forêts, G. 2000, A&A, 356, 1039

Ward-Thompson, D., Motte, F., & André, P. 1999, MNRAS, 305, 143

Womack, M., Ziurys, L. M., & Sage, L. J. 1993, ApJ, 406, L29

Yokogawa, S., Kitamura, Y., Momose, M., & Kawabe, R. 2003, ApJ, 595, 266

Zhou, S., Evans, N. J., II, Wang, Y., Peng, R., & Lo, K. Y. 1994, ApJ, 433, 131