Low-Mass Star-Forming Cores in the GF 9 Filament

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Abstract

We carried out an unbiased mapping survey of dense molecular cloud cores traced by the NH$_3$ (1,1) and (2,2) inversion lines in the GF 9 filament, which contains an extremely young low-mass protostar, GF 9-2 (2006, ApJ, 653, 1369). The survey was conducted using the Nobeyama 45 m telescope over a region of $\sim 1.5 \times 1^\circ$ with an angular resolution of 73$''$. The large-scale map revealed that the filament contains at least 7 dense cores, as well as 3 possible ones, located at regular intervals of $\sim 0.9$ pc. Our analysis shows that these cores have kinetic temperatures of $\lesssim 10$ K and LTE-masses of $1.8-8.2M_\odot$, which makes them typical sites of low-mass star formation. All of the identified cores are likely to be gravitationally unstable, because their LTE-masses are larger than their virial masses. Since the LTE-masses and separations of the cores are consistent with the Jeans masses and lengths, respectively, for the low-density ambient gas, we argue that the identified cores formed via the gravitational fragmentation of the natal filamentary cloud.

Key words: ISM: clouds — ISM: evolution — ISM: individual (GF 9, L 1082) — ISM: molecules — stars: formation — stars: pre-main sequence

1. Introduction

A filamentary dark cloud often provides a unique opportunity to investigate the formation and evolution of a dense cloud core, the birthplace of low-mass stars, through fragmentation processes. The dense cores appear to maintain themselves as substructures in the parental cloud, which is known to be mostly governed by supersonic turbulence. The dense cores usually exhibit supersonic line widths; the turbulence prevents gravitational collapse of the cores. It is now widely accepted that turbulence plays a fundamental role in controlling the core-formation processes (e.g., Mac Low & Klessen 2004; Ballesteros-Paredes et al. 2007 for reviews and references therein). Possible mechanisms for core formation and collapse have a widespread range of from a gradual release of magnetic support (e.g., Shu et al. 1987) to a dynamical dissipation of turbulent waves (e.g., Larson 1981; Ostriker et al. 2001; Padoan & Nordlund 2002). Although we have now a good overall picture of the theory of low mass star formation (e.g., McKee & Ostriker 2007), observational verification of the way dense cores form and collapse has produced limited success.

There have been quite a few observational studies which have assessed the initial conditions for the gravitational collapse of a dense core. The low-mass protostar GF 9-2 with bolometric luminosity and temperature values of $\sim 0.3L_\odot$ and $\lesssim 20$ K, respectively (Wiesemeyer 1997), remains the best-characterized extremely young protostar that would be a missing link between starless cores and Class 0 protostars. The natal core of GF 9-2 is believed to retain the initial conditions of the gravitational collapse because the central protostar has not launched an extensive outflow. Namely, the core has not yet been destroyed by an extensive outflow (Furuya et al. 2006; hereafter paper I). Our detailed analysis suggested that the core has undergone its gravitational collapse for $\sim 2 \times 10^5$ yr (the free-fall time) from an initially unstable state (Larson 1969; Penston 1969; Hunter 1977), and that the protostar formed $\lesssim 5 \times 10^3$ yr ago. Note that the GF 9-2 core is cross-identified as L 1082C in Benson and Myers (1989, hereafter BM89), LM 351 in Lee and Myers (1999, hereafter LM99), and GF 9-Core in Ciardi et al. (2000); the central Young Stellar Object (YSO) is also recognized as PSC 20503+6006.

Besides the presence of GF 9-2, the filamentary dark cloud GF 9 (Schneider & Elmegreen 1979) would be an ideal laboratory to establish a core-formation scenario through the fragmentation of a filamentary cloud, because an ISO imaging survey in the far-infrared has demonstrated the presence of several Class 0 and I sources (Wiesemeyer 1997; Wiesemeyer et al. 1999). Toward our ultimate goal of defining an observational framework for cloud core formation, the first step is to investigate the physical properties of dense cores formed in the filament. We therefore performed an unbiased survey of dense cores in the GF9 filament. The filament has an
Fig. 1. Total integrated intensity map of the NH$_3$ (1,1) emission observed with the Nobeyama 45 m telescope. We integrated the main group of the hyperfine emission over the velocity range $-3.2 \leq V_{LSR}/$km s$^{-1} \leq -1.4$ (see subsection 3.1 for details). The contour intervals are the 3$\sigma$ levels, starting from the $6\sigma$ level, where the $1\sigma$ noise level is 37.0 mK km s$^{-1}$ in $T_{mb}$. The map origin is RA = 20$^{h}$18$^{m}$30$^{s}$, Dec = 60$^\circ$18$'$38$''$ in J2000.0. The peak positions of the identified cores and their identification numbers by previous work are summarized in table 1. The thick black labels indicate the designation numbers of the cores, while the blue thin labels the candidate cores. The open blue circles indicate the areas to which the 45 m telescope beam was pointed for deep integration (section 2). Note that the size of the open blue circles is the same as the effective beam size of the map ($\theta_{eff} = 100''$, see section 2), which is shown by the hatched circle in the bottom-left corner. The open purple triangles and red stars with the labels indicate the positions of the “embedded YSOs” identified in Lee and Myers (1999) and the IRAS sources, respectively.

2. Observations and Data Reduction

We carried out simultaneous observations of the NH$_3$ (1,1) and (2,2) lines using the Nobeyama Radio Observatory (NRO)$^1$ 45 m telescope over 16 d in 2006 April. We used the 22 GHz cooled HEMT receiver (H22), which receives right- and left-hand circular polarization components simultaneously. The beamwidth ($\theta_{HPBW}$) and the main-beam efficiency ($\eta_{mb}$) of the telescope were $73'' \pm 0''2$ and $83 \pm 5\%$, respectively, at 23.0 GHz. To obtain dual polarization data of the (1,1) line, we configured two Auto Correlator (AC) spectrometers having 8 MHz band width with 1024 channels; the newly enhanced capability provided us with 3 times higher velocity resolution than the previous one. After on-line smoothing with the Hamming window function, the effective velocity resolution ($\Delta v_{res}$) for the NH$_3$ (1,1) lines is 0.180 km s$^{-1}$. For the (2,2) transition, we used two acousto-optical spectrometers (AOSs), which provide $\Delta v_{res}$ of 0.494 km s$^{-1}$. Here, we adopt rest frequencies of 23694.4955 MHz for the (1,1) transition (Ungerechts et al. 1980, hereafter UWW80) and 23722.6336 MHz for the (2,2) (Lovas 1992) transition.

We performed mapping observations under full-beam sampling to cover the whole region of the GF9 cloud previously imaged with the H$_2$CO $1_{01-1_{01}}$ absorption line (Güsten 1994). Using a position-switching mode, we observed a total of 766 points by dividing the filament into 8 rectangular regions; each region was mapped with a grid spacing of 80'' in R.A. The telescope pointing was checked every 4 hr, and was found to be accurate to within 5''. The daily variation of the H22 receiver gain was checked by the peak antenna temperature ($T_{A}^*$) of the NH$_3$ (1,1) emission toward the GF9-2 core center. We estimate that the final uncertainty in flux calibration is 22%. All

$^1$ Nobeyama Radio Observatory is a branch of the National Astronomical Observatory of Japan, National Institutes of Natural Sciences.
of the spectra were calibrated by the standard chopper wheel method, and converted into the main-beam brightness temperature \( T_{\text{mb}} = T^*_A/\theta_{\text{mb}}^2 \) scale. At the final stage of spectral data reduction, the dual polarization data were concatenated to increase the signal-to-noise ratio \( S/N \). Subsequently, we made a total integrated intensity map with an effective resolution of \( \theta_{\text{eff}} = 100'' \) from smoothed velocity channel maps by a Gaussian function with \( \theta_{\text{HPBW}} = 68'' \).

In addition, we performed deep single-point integrations toward the approximate center positions of 9 cores on the basis of preliminary \( \text{NH}_3 \) maps made during mapping observations. These deep integrations were intended to obtain a better estimate of the intensity ratio of the (1,1) to (2,2) transition, and gave a 4–5 times lower noise level than that in the mapping observations.

3. Results and Analysis

In this section, we present the total integrated intensity map of the \( \text{NH}_3 \) (1,1) emission, as well as the (1,1) and (2,2) spectra obtained through deep integrations. Since the (2,2) emission was detected only toward the GF-9-2 and 9 core centers, we do not present a map of the transition.

3.1. Identification of Dense Cloud Cores in the Filament

Figures 1 and 2 show total integrated intensity maps of the \( \text{NH}_3 \) (1,1) emission for the whole filament and individual cores, respectively. Here, we integrated the main group of the hyperfine (HF) emission (Wilson et al. 1978; UWW80) between \( V_{\text{LSR}} = -3.2 \text{ km s}^{-1} \) and \( -1.4 \text{ km s}^{-1} \). To find the velocity range, we made figure 3, where we present the LSR-velocity ranges of the main HF groups for the 9 spectra (figure 4) taken with the deep integrations (section 2). The velocity range for each core is defined by the two LSR-velocities where the intensity of the main HF group drops to the 1.5\( \sigma \) level. All of 9 spectra showed similar velocity ranges; the most blue- and redshifted velocities are found to be \( V_{\text{LSR}} = -3.21 \text{ km s}^{-1} \) in core 9 and \( -1.36 \text{ km s}^{-1} \) in core 8, respectively.

Figure 1 clearly shows the presence of 7 dense cloud cores, labeled \( \text{GF}9-5 \), 8, 4, 3, 2, 1, and 9 from east to west; table 1 summarizes the peak positions of the cores, together with other names found in the literature. The peak \( T_{\text{mb}} \) of these cores exceeds our detection threshold of \( S/N = 6 \), which means \( S/N \geq 3 \) for the 50\% level contour with respect to the peak intensity. Notice that each core is detected at only a few observing points, as seen in figure 2. Figure 2f shows that the two core candidates, GF-9-6 and 10, have peak intensities of \( 3 \leq S/N < 6 \). They are probably real objects because they seem to contain IRAS sources within the 3\( \sigma \) level contours. The GF-9-10 core may be a new detection, although we have to verify its presence by obtaining a better \( S/N \). Although the GF-9-7 core candidate can be marginally recognized above the 3\( \sigma \) level in figure 2g, we clearly detected (1,1) emission through the deep integration (figure 4g). The GF-9-2, 3, and 4 cores were detected in \( \text{NH}_3 \) (1,1) with the Haystack 37 m telescope (\( \theta_{\text{HPBW}} \sim 87'' \): BM89), and were designated as L1082C, A, and B, respectively. The GF-9-8 core is also seen in figure 33 of BM89, but these authors have not given the core an identification number. The GF-9-8 core has not been observed in \( \text{NH}_3 \) mapping with the Effelsberg 100 m telescope (\( \theta_{\text{HPBW}} = 40'' \): Wiesemeyer 1997). It is interesting that the GF-9-5 and 8 cores as well as the GF-9-7 core candidate do not exhibit YSO activity, suggestive of starless cores.

No dense core was detected toward the “embedded YSO” of LM349 (LM99), while the two “embedded YSOs” of
LM 350 and 351 are associated with the NH$_3$ cores. Here, an “embedded YSO” is a far-infrared bright YSO selected from the IRAS point-source catalog (see LM99 for definition). The relationship between the remaining “embedded YSO” of LM 352 and the GF 9-4 core is not clear (see figure 2d). The absence of an NH$_3$ core around LM 349 implies that the “embedded YSO” may be a very low-mass object, whose core mass is too small to be detected by our mapping survey. We also point out that LM 349 is close to one of the local peaks in the $^{13}$CO (1–0) column density map of Ciardi et al. (2000; see also figure 1 of Poidevin & Bastien 2006).

It is worth noting that the IRAS sources located in the GF 9-3 and 4 cores are driving weak molecular outflows with momentum rates of $F_{CO} \sim 10^{-5} - 10^{-6} M_\odot$ km s$^{-1}$ yr$^{-1}$. (Bontemps et al. 1996), approximately along the north–south direction.

Last, it is likely that the number density of the cores tends to become high toward the east, while low to the west. In fact, the four cores in the eastern part of the filament, GF 9-3, 4, 5, and 8, seem to be confined to a rather small region of $\sim 0.8$ pc. Since the mean separation between the two neighboring cores is 0.36 pc, they can be treated as a group of cores. Similarly, we consider the GF 9-6 and 10 core candidates as another group. Here, the separations were calculated using the peak positions given in table 1. Consequently, the two core groups, the isolated GF 9-2, 1, and 9 cores, and the candidate core GF 9-7 are located at regular intervals of $\sim 0.9$ pc.

3.2. NH$_3$ Spectra toward the Cores

Figure 4 presents 9 spectra of the NH$_3$ ($J, K$) = (1,1) and (2,2) rotation inversion lines obtained by the deep integrations (section 2). All of the observed positions showed intense (1,1) emission with the distinct five groups of the HF components, except for GF 9-7, where the inner satellite HF groups at $v_{LSR} \sim +6$ km s$^{-1}$ and $-10$ km s$^{-1}$ are barely recognized. Notice that the NH$_3$ spectra for the core candidates GF 9-6 and 7 were not taken toward the exact peak positions of the cores (see figures 2f and 2g).

In contrast to the (1,1) lines, the sole main HF group of the (2,2) transition was detected toward only GF 9-2 and 9 with S/N $\geq 3$. Given the attained S/N in our observations, nondetection of the satellite (2,2) HF groups does not give a stringent limit to the optical depth, namely, $\tau_{22} \leq 7$, since the intrinsic ratio of the main-to-satellite groups is about 15.9 for the (2,2) transition (Wilson et al. 1978). Nevertheless, we believe that the (2,2) lines are optically thin because the observed $T_{mb}$ is considerably lower than the excitation temperature of the (1,1) transition, $T_{exc}$ (1,1) (7.4–9.5 K; described in subsection 3.3).

### Table 1. Peak positions of the NH$_3$ cores including the candidates in the GF 9 filament.

| GF 9-1 | Other identifications | Peak position$^\dagger$ | Associated $^\dagger$ |
|--------|-----------------------|-------------------------|-----------------------|
| W99    | BM89                  | RA (J2000.0)            | Dec (J2000.0)         |
| 5 core | GF 9-5                | $20^{h}54^{m}01^{s}$   | $60^{d}24^{m}9^{s}$   | IRAS 20520+6003 |
| 3 core | GF 9-3A/3B L 1082A     | $20^{h}53^{m}25^{s}$   | $60^{d}14^{m}11^{s}$  | IRAS 20526+5958, LM 352 |
| 4 core | GF 9-4                | $20^{h}53^{m}49^{s}$   | $60^{d}09^{m}30^{s}$  | IRAS 20526+5958, LM 352 |
| 8 core | ...                   | $20^{h}53^{m}52^{s}$   | $60^{d}17^{m}10^{s}$  | ... |
| 2 core$^5$ | GF 9-2 L 1082C     | $20^{h}51^{m}29^{s}$   | $60^{d}18^{m}34^{s}$  | IRAS 20520+6003 |
| 1 core | GF 9-1                | $20^{h}49^{m}50^{s}$   | $60^{d}15^{m}52^{s}$  | LM 350 |
| 9 core | GF 9-16               | $20^{h}47^{m}57^{s}$   | $60^{d}03^{m}24^{s}$  | IRAS 20468+5953 |
| 6    | GF 9-6                | $20^{h}47^{m}05^{s}$   | $59^{d}51^{m}18^{s}$  | IRAS 20460+5939 |
| 10   | ...                   | $20^{h}46^{m}28^{s}$   | $59^{d}48^{m}53^{s}$  | IRAS 20454+5938 |
| 7    | GF 9-7                | $20^{h}48^{m}11^{s}$   | $59^{d}39^{m}25^{s}$  | ... |

$^*$ GF 9 core designation numbers with “core” are for firm detections, while the others without “core” for possible detections. See subsections 3.1 and 3.3 for details. We used the same designation number for the cores used in Wiesemeyer et al. (1999) to keep consistency as much as possible. Notice that the above core numbers are different from the GF 9 star designation numbers with upper-case S given in Poidevin and Bastien (2006).

$^\dagger$ References — W99: Wiesemeyer et al. (1999); BM89: Benson and Myers (1989).

$^\ddagger$ The errors in the absolute positions, due to the telescope pointing error (see section 2), are typically 5".

$^5$ GF 9-2 core is also identified as GF 9-Core in Ciardi et al. (2000).
Fig. 4. Spectral profiles of the NH$_3$ (1,1) and (2,2) rotational inversion lines at the peak positions, except for GF9-6, of the identified cores and the candidates (see subsection 3.1) obtained through the deep integration (section 2). All of the (2,2) spectra are magnified three times. Notice that the spectrum toward GF9-6 in panel (f) has not been obtained at the center position of the core (see figure 2f), and that no deep integration has been carried out toward the GF9-10 core. The 1σ rms noise levels shown for each spectrum are given in $T_{mb}$ scale.
3.3. Hyperfine Structure Analysis and Column Density Calculations

It is difficult to accurately know how each core extends, because our survey observations were conducted with full-beam sampling. We therefore limited our analysis to the peak spectra that had a sufficient S/N, instead of making source-averaged spectra. To calculate beam-averaged NH$_3$ column densities ($N_{NH}_3$), we employed hyperfine structure (HFS) analysis, which gave the total optical depth ($\tau_{tot}$), the velocity width ($\Delta v_{FWHM}$), and the LSR velocity of one of the HF components ($v_0$). Here, $\Delta v_{FWHM}$ is the FWHM of a single HF component, and is assumed to be identical for all of the HF components, and $\tau_{tot}$ is defined by the sum of the optical depths of all HF components. The $\Delta v_{FWHM}$ was subsequently deconvolved with the instrumental velocity resolution (section 2) to estimate an intrinsic velocity width ($\Delta v_{int}$). It should be noted that $\Delta v_{int}$ was free from a velocity-width increase caused by a high optical depth, because our HFS analysis solved the procedure used in paper I; our analysis was essentially equivalent to that summarized in Stutzki and Winnewisser (1985) and other papers of, e.g., Winnewisser, Churchwell, and Walmsley (1979), UWW80, Pauls et al. (1983), and Ungerechts, Walmsley, and Winnewisser (1986).

First, we fitted one Gaussian profile to the main HF group of the (1,1) and (2,2) spectra. Table 2 summarizes the obtained peak temperatures in $T_{mb}$, which were used to calculate the rotational temperature of the (1,1) and (2,2) levels ($T_{r,21}$) in the third step. Second, we performed an HFS analysis of the (1,1) spectra. The resultant parameters of $v_0$, $\Delta v_{int}$, and $\tau_{tot}$ are summarized in table 2; these $\Delta v_{int}$ values are plotted in figure 3 as well. Third, using equation (4) of Ho and Townes (1983), we calculated $T_{r,21}$ with the above peak $T_{mb}$ values for both the transitions and $\tau_{tot}$. To use the equation, we gave the mean optical depth of the (1,1) line by $\tau_{tot}/18$, where the denominator of 18 is the number of (1,1) HF components (e.g., UWW80). For the 7 cores where the (2,2) transition was not detected, we adopted the $3\sigma$ upper limit as a peak $T_{mb}$. Table 2 shows that $T_{r,21}$ was calculated to be 7.4 ± 0.3 K for GF9-2 and 7.9 ± 0.4 K for GF9-9, while the other cores have upper limits ranging between 7.1 K and 12.8 K. Fourth, given $\tau_{tot}$, $\Delta v_{int}$, and excitation temperature ($T_{ex}$), we calculated the beam-averaged column density of NH$_3$ molecules in the (1,1) level, $N_{11}$, leading to $N_{NH}_3$ with the $T_{r,21}$ value. For this purpose, we used equation (2) in UWW80. We assumed that all of the energy levels are in LTE at temperature $T_{r,21}$, and that $T_{r,21}$ is equal to $T_{ex}$ as well as the gas kinetic temperature ($T_k$) of the core, i.e., $T_{r,21} = T_{ex} = T_k$. The cores are dense ($n_{H}_3$ = 10$^5$ cm$^{-3}$) enough to make our assumption valid (Stutzki & Winnewisser 1985; Taffeta et al. 2004). We believe that this assumption is reasonable, because the derived $T_{r,21}$ agrees well with $T_{ex}$ of C$^{18}$O (1–0) (7–8 K for GF9-2, 3, and 4: Myers et al. 1983), $^{13}$CO (1–0) (7.2 K for GF9-2: Ciardi et al. 2000), and N$_2$H$^+$ (1–0) (9.5 K: paper I). We consequently obtained the NH$_3$ column densities, as summarized in Table 3. Here, we exclude the candidate cores No. 6, 7, and 10 with insufficient S/N. We found that the error in $\tau_{tot}$ and the possible uncertainty in $T_{ex}$ of 7.4–9.5 K caused uncertainties in $N_{11}$ ranging from 3% (GF9-2) to 33% (GF9-5).

Last, we verified whether or not the above results toward the GF9-2 core are consistent with those obtained from the spectra with the coarse velocity resolution in paper I (see the core center portions of tables 5 and 6). It should be noted that the optical depth given in table 5 of paper I is that for the most intense HF component, which can be converted into a $\tau_{tot}$ of 6.8 ± 0.4; the value does not significantly differ from the new value of 8.0 ± 0.2 in this work. The high-velocity resolution in this study gives an ~1.5 times narrower $\Delta v_{int}$ than

| Core | $T_{mb}$ (mK) | $v_0$ (km s$^{-1}$) | $\Delta v_{int}$ (km s$^{-1}$) | $\tau_{tot}$ (K) | $T_{mb}$ (mK) | $T_{r,21}$ (K) |
|------|--------------|-----------------|----------------|----------------|--------------|-------------|
| 1    | 860 ± 50     | −2.53           | 0.37 ± 0.02    | 4.4 ± 0.5      | ≤ 72         | ≤ 7.1       |
| 2    | 1270 ± 90    | −2.52           | 0.39 ± 0.01    | 8.0 ± 0.2      | 110 ± 9      | 7.4 ± 0.3   |
| 3    | 740 ± 55     | −2.23           | 0.42 ± 0.02    | 6.0 ± 0.7      | ≤ 69         | ≤ 7.6       |
| 4    | 630 ± 40     | −2.36           | 0.31 ± 0.02    | 6.9 ± 0.9      | ≤ 62         | ≤ 7.8       |
| 5    | 320 ± 25     | −2.32           | 0.39 ± 0.03    | 1.8 ± 0.6      | ≤ 29         | ≤ 9.7       |
| 6    | 310 ± 20     | −2.42           | 0.28 ± 0.02    | 2.1 ± 0.6      | ≤ 29         | ≤ 10.1      |
| 7    | 160 ± 12     | −2.14           | 0.50 ± 0.08    | 2.0 ± 1.3      | ≤ 40         | ≤ 12.8      |
| 8    | 630 ± 50     | −2.15           | 0.34 ± 0.02    | 8.4 ± 1.0      | ≤ 87         | ≤ 7.9       |
| 9    | 600 ± 45     | −2.61           | 0.43 ± 0.02    | 6.3 ± 0.6      | 57 ± 6       | 7.9 ± 0.4   |

* We analyzed the peak spectra shown in figure 4 (see subsection 3.3 for details).
† All of the spectra, except for the core candidates of #6 and #7, were taken towards the center positions of the identified cores (see figure 2).
‡ Peak $T_{mb}$ for the main group of the hyperfine emission obtained by single Gaussian fitting. The upper limits for the (2,2) transition are the $3\sigma$ upper limits (see figure 4 as well).
§ $v_0$, $\Delta v_{int}$, and $\tau_{tot}$ denote the centroid velocity, the intrinsic velocity width after correcting for the instrumental velocity resolution, and the total optical depth obtained from the hyperfine structure analysis, respectively (see subsection 3.3 for details). The errors for $v_0$ are typically less than 0.01 km s$^{-1}$.
‖ Rotational temperature of NH$_3$ molecules between the (1,1) and (2,2) states (see subsection 3.3).
that in previous work. The most significant difference between the two studies is that the new observations have succeeded in detecting the (2,2) transition, leading to the low $T_{\text{r,21}}$ values. In other words, the cold temperature is the main cause of the higher $N$(NH$_3$), by a factor of $\sim 3$ compared with paper I.

3.4. LTE Masses of the Cores

Once the beam-averaged $N_{\text{NH}_3}$ had been obtained, we could calculate the LTE-mass, $M_{\text{LTE}}$, within the beam by supplying the fractional abundance of NH$_3$ molecules, $X$(NH$_3$). We assumed that $X$(NH$_3$) = $(2 \pm 1) \times 10^{-8}$, estimated in GF9-2 (paper I), is valid for the other cores. Notice that, as addressed in paper I, the adopted abundance is in reasonable agreement with those in similar objects (Jijina et al. 1999). The resultant $M_{\text{LTE}}$ ranges from $1.8M_\odot$ (GF9-5) to $8.2M_\odot$ (GF9-2) (table 3). Although the LTE-mass for GF9-2 seems to be twice the previous estimate of $4.5 \pm 2.4M_\odot$ (paper I), the two measurements can be reconciled by considering the $\sim 50\%$ uncertainty in $X$(NH$_3$) and the difference between the adopted core sizes ($5.5 \times 10^{-3}$ pc$^2$ in paper I, versus $3.9 \times 10^{-3}$ pc$^2$ in this work). Notice that the $\sim 50\%$ uncertainty in $X$(NH$_3$) causes a significantly larger error in $M_{\text{LTE}}$ than those from the uncertainties in $T_{\text{r,rot}}$ and $T_{\text{ex}}$, described in the previous subsection.

3.5. Velocity Widths and Virial Masses of the Cores

In table 2, we summarize the $\Delta v_{\text{th}}$ values obtained through the HFS analysis. Clearly, the observed intrinsic velocity widths in all of the cores are 2–3 times larger than $\Delta v_{\text{th}}$ of 0.16–0.18 km s$^{-1}$ for the $T_{\text{K}}$ range of 7.4–9.5 K $\{\Delta v_{\text{th}} = [8\ln 2kT_K/m_{\text{NH}_3}]^{1/2}\}$. This fact indicates that the internal motions of all the cores are dominated by nonthermal pressure ($\Delta v_{\text{nth}}$), such as supersonic turbulence. Assuming that the nonthermal motions as well as the thermal ones support the cores against their self-gravity, we calculated the virial masses ($M_{\text{vir}}$; see table 3) using $\Delta v_{\text{vir}}$ in table 2. In subsection 4.1, we compare $M_{\text{LTE}}$ with $M_{\text{vir}}$ in the context of the dynamical instability of the cores.

### Table 3. Properties of the ammonia cores in the GF9 filament.

| Core | $M_{\text{vir}}$ (M$_\odot$) | $N$(NH$_3$) (x10$^{15}$ cm$^{-2}$) | $M_{\text{LTE}}$ (M$_\odot$) |
|------|-----------------|----------------------|------------------|
| 1    | 1.0 ± 0.09      | 1.0 ± 0.2            | 4.3 ± 2.1        |
| 2    | 1.1 ± 0.03      | 2.0 ± 0.3            | 8.2 ± 4.1        |
| 3    | 1.3 ± 0.16      | 1.6 ± 0.3            | 6.7 ± 3.3        |
| 4    | 0.7 ± 0.08      | 1.4 ± 0.3            | 5.7 ± 2.9        |
| 5    | 1.1 ± 0.18      | 0.4 ± 0.1            | 1.8 ± 0.9        |
| 6    | 0.9 ± 0.09      | 1.8 ± 0.3            | 7.5 ± 3.8        |
| 7    | 1.3 ± 0.12      | 1.7 ± 0.4            | 7.1 ± 3.6        |

* Virial mass of the cores calculated from $M_{\text{vir}} = \frac{1}{2} \frac{\text{d}(\Delta v_{\text{th}})}{\text{d}^2}$ (see subsection 3.5).

† Beam-averaged NH$_3$ column density; the errors are calculated from the possible $T_{\text{ex}}$ range of 7.4–9.5 K and the uncertainties in $T_{\text{r,rot}}$ and $\Delta v_{\text{th}}$.

‡ LTE-mass of the cores calculated from $M_{\text{LTE}} = \mu_B m_{\text{H}} \frac{N$(NH$_3$)}{N$(\text{NH}_3)$} \frac{\pi d^2}{2} c_{141}$ (see subsection 3.4). Here, $\mu_B$ denotes the mean molecular weight of 2.33 and $m_{\text{H}}$ the atomic mass of hydrogen. The errors are due to the $\sim 50\%$ uncertainty in $X$(NH$_3$).

4. Discussion

4.1. Gravitational Instability of the Cores

It is probable that all of the cores in the GF9 filament are gravitationally unstable, because $M_{\text{vir}} < M_{\text{LTE}}$ (table 3), if we interpret that the nonthermal velocity widths are due to supersonic turbulence within the cores. Here, another distance estimate of 440 pc (section 1) does not alter the relationship of $M_{\text{vir}} < M_{\text{LTE}}$, because $M_{\text{vir}}$ is proportional to $d$, while $M_{\text{LTE}}$ varies with $d^2$. To verify the interpretation, we should assess the origin of the nonthermal widths, as done in Ciardi et al. (2000) and paper I. In addition to the turbulent motions, it is well-known that spectral line profiles can be broadened beyond their thermal widths owing to systematic motions of gas, such as stellar winds or/and infall. However, it is unlikely that $\Delta v_{\text{nth}}$ arises primarily from supersonic stellar winds or outflows because, to our knowledge, the NH$_3$ inversion lines do not trace molecular outflows, but static dense gas.

We suggest that the nonthermal velocity widths of the cores are produced by large-scale infall motions, rather than turbulent ones. In fact, we discussed the presence of the supersonic infalling motions all over the GF9-2 core in paper I. Our recent follow-up observations have clearly detected blueskewed profiles in the optically thick HCO$^+$ (3–2) and (1–0) lines over the GF9-2 core. Moreover, we have detected such blue-skewed profiles toward the peak positions of the GF9-4, 8, and 9 cores with the (3–2) transition. These facts reinforce the idea that the internal motions of the cores in the GF9 filament are dominated by the large-scale supersonic infalling motions, although we have to assess the presence of the infall in all of the cores through mapping observations. If this interpretation is valid for all of the cores, $M_{\text{vir}}$ should be calculated solely with the thermal width, i.e., $M_{\text{vir,thm}} = [5/(32\ln 2)] \cdot (\theta_{\text{HPBW}}/G) \cdot (kT_k/\mu m_{\text{H}})$, yielding 0.19–0.25 $M_\odot$ for the $T_{\text{ex}}$ range of 7.4–9.5 K. This estimate suggests that most of the cores should be gravitationally unstable, because $M_{\text{vir,thm}} < M_{\text{LTE}}$ in spite of the $\sim 50\%$ uncertainty in $M_{\text{LTE}}$.

4.2. Formation of the Cores in the Filament

A gravitational fragmentation process can explain why the dense cores in the GF9 filament are located at regular intervals of $\sim 0.9$ pc (see figure 1). Recall that we consider the GF9-5, 8, and 4 cores, as well as the GF 9-6 and 10 core candidates, as groups (subsection 3.1). For the sake of simplicity, we compare the core separation with an expected Jeans length ($\lambda_J$) for the filament. Ciardi et al. (2000) estimated a density of $n_{\text{H}_2} = 1700 \pm 200$ cm$^{-3}$ for the GF9 filament from their $^{13}\text{CO}$ (1–0) observations. Assuming that the ambient gas has a typical density of $\sim 10^3$ cm$^{-3}$, $\lambda_J$ is computed to be $\sim 0.6$ pc at $T_k = 10$ K. This estimate is not significantly different from the core separation of $\sim 0.9$ pc. Here, the temperature of 10 K is taken from the typical peak $T_{\text{inh}}$ (6–7 K) of the optically thick $^{12}\text{CO}$ (3–2) and (1–0) emission derived in the ambient gas around the GF9-2 core (paper I). In addition, the Jeans mass for $T_k = 10$ K and $n_{\text{H}_2} \sim 10^3$ cm$^{-3}$ was calculated to be $\sim 3M_\odot$, which is comparable to the core LTE-masses (table 3). Such an estimate based on the “classical” Jeans analysis implies that the fragmentation of the filament has been caused by the gravitational instability.
Alternatively, the spatial distribution of the identified cores might be understood in terms of the magnetohydrodynamical instability of the G9 filamentary cloud, as Hanawa et al. (1993) proposed for interpreting the ongoing fragmentation process in the Orion A filamentary cloud. They discussed that the effective sound velocity increases when the effect of the magnetic field and/or rotation is considered [see their equation (11)], and that the Jeans length of the filament becomes as short as the core separation, unless the filament is almost perpendicular to the plane-of-sky. The apparent configuration of the G9 filament would be somewhat similar to that of the Orion cloud. However, to make such a comparison, we need to know not only basic parameters characterizing the filament, such as the length, width, inclination angle, and total mass, but also the magnetic field strength and/or velocity field.

5. Summary

Using the Nobeyama 45 m telescope, we carried out an unbiased survey of dense molecular cores in the G9 filament. The obtained large-scale map of the NH$_3$ (1,1) emission revealed that the filament contains 7 dense ($n_{H_2} \sim 10^4$ cm$^{-3}$) and cold ($T_k \lesssim 10$ K) cores having the LTE-masses of 1.8–8.2$M_\odot$, and three candidates located at regular intervals of $\sim 0.9$ pc. We argued that these cores appear to be gravitationally unstable, and have formed through the gravitational fragmentation of the natal filamentary cloud. Further high-resolution imaging of the identified cores, as well as a search for blue-skewed infall profiles over the cores, will allow us to discuss the physical properties of the cores on more solid ground. We lastly point out that good knowledge of the velocity field of the low-density intercore gas traced by, e.g., the $^{13}$CO (1–0) line, will provide us with an essential clue toward understanding the formation mechanism of star-forming cores in a filamentary cloud.

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