INTERNAL MOTIONS IN STARLESS DENSE CORES

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ABSTRACT

This paper discusses the statistics of internal motions in starless dense cores and the relation of these motions to core density and evolution. Four spectral lines from three molecular species are analyzed from single-pointing and mapped observations of several tens of starless cores. Blue asymmetric profiles are dominant, indicating that inward motions are prevalent in sufficiently dense starless cores. These blue profiles are found to be more abundant, and their asymmetry is bluer, at core positions with stronger N\textsubscript{2}H\textsuperscript{+} line emission or higher column density. Thirty-three starless cores are classified into four different types according to the blueshift and redshift of the lines in their molecular line maps. Among these cores, contracting motions dominate: 19 are classified as contracting, 3 as oscillating, 3 as expanding, and 8 as static. Contracting cores have inward motions all over the core with those motions predominating near the region of peak density. Cores with the bluest asymmetry tend to have greater column density than other cores and all five cores with peak column density $> 6 \times 10^{21}$ cm$^{-2}$ are found to be contracting. This suggests that starless cores are likely to have contracting motions if they are sufficiently condensed. Our classification of the starless cores may indicate a sequence of core evolution in the sense that column density increases from static to contracting cores: the static cores in the earliest stage, the expanding and/or the oscillating cores in the next stage, and the contracting cores in the latest stage.

Key words: ISM: clouds – ISM: kinematics and dynamics

Online-only material: color figures

1. INTRODUCTION

“Starless” dense ($n_{\text{H}_2} \geq 10^4$ cm$^{-2}$) cores are the cores which have no embedded protostars or no associated T-Tauri stars (Lee \& Myers 1999). Such cores have no internal outflows and are well separated from external triggering effects such as outflows and winds from other stars, or supernova explosions. Therefore, they are the best laboratory to explore initial conditions of isolated star formation (e.g., Ward-Thompson 2002). Internal motions in starless cores can indicate contraction, a sign of physical progress toward star formation. Ambipolar diffusion or dissipation of turbulence may drive such motions (e.g., Ciolek \& Mouschovias 1995; Nakano 1998; Myers \& Lazarian 1998). However, it is not conclusive yet which mechanisms lead the collapse of the cores to eventually form a protostar in the cores.

The presence of contracting or expanding motions along the line of sight has been inferred from spectroscopic observations of optically thick and thin molecular lines. The “spectral infall asymmetry” is a combination of a pair of spectral line shapes. A double-peaked shape with a blue peak brighter than a red peak occurs in a thick line, while a single Gaussian-like shape occurs in a thin line. This combination is often used to trace “inward” motions of gaseous material in starless cores (Leung \& Brown 1977; Zhou 1995; Myers et al. 1996). Since the infall asymmetry in starless core was first reported in L1544 (Tafalla et al. 1998), it has been observed in numerous starless dense cores using thin (such as N\textsubscript{2}H\textsuperscript{+} 1–0) and thick (such as CS 2–1, CS 3–2, and HCN 1–0) molecular lines, finding that inward motions are a dominant feature in starless cores (Lee et al. 1999, 2004; Sohn et al. 2007).

Mapping observations of starless cores also indicated that the infall asymmetry is spatially extended comparable to the size of the N\textsubscript{2}H\textsuperscript{+} cores (Tafalla et al. 1998; Lee et al. 2001, hereafter LMT01). The most extensive mapping survey of starless cores to study a pattern of inward motions was given by LMT01. Out of 53 starless cores observed in both of N\textsubscript{2}H\textsuperscript{+} 1–0 and CS 2–1 lines, 19 infall candidates were selected according to the spectral shapes of CS 2–1 lines, and the velocity shift of their brighter component from the velocity of the systemic component traced by the optically thin N\textsubscript{2}H\textsuperscript{+} line. This survey showed that extended inward motions are a frequently occurring feature in starless cores and are probably a necessary process in the condensation of a star-forming dense core.

On the other hand, mapping studies have also indicated that gaseous motions could be more complex in some cores than “all inward.” Some starless cores showed overabundance of red asymmetric profiles (e.g., L429-1 and CB246 from LMT01 and FeSt1-457 from Aguti et al. 2007). Just as the blue asymmetric profiles indicate inward motions, the cores showing red asymmetric profiles are likely to be expanding. The origin of such expansion is unclear. One suggested idea for the existence of red asymmetric profiles in a dense core is that some disturbance in the external pressure of the core under the state of gravitational equilibrium (such as shock waves caused by nearby OB stars or supernovae) may trigger its oscillatory motions in the outer layers and the core is now being observed in the state of expanding motion (e.g., Lada et al. 2003; Redman et al. 2006; Aguti et al. 2007). Other starless cores (L1495A-N, L1507A, and L1512 from LMT01 and B68 from Redman et al. 2006) show a complicated mixture of blue and red asymmetric profiles. Oscillating motions of some specific mode in gaseous outer layers of the cores were also suggested to explain this feature (e.g., Lada et al. 2003; Broderick \& Keto 2010).

Of course, there are some cores which do not show any significant asymmetric feature in lines, i.e., no evidence of large-scale contraction or expansion.

The foregoing results raise several basic questions about core motions and about how such motions are distributed in a sample...
we discuss the implication of the distribution of the lines and its relation to physical quantities. In the last section the context of dense core evolution and the environmental effect on surveys of starless cores in CS 2–1 and N2H+ 1–0 (Lee et al. obtained from several previous observations, single-pointing observations toward central regions of the cores and mapping observations fully covering the cores. Column 4 gives the number of sources detected with each observing line in Column 1. Here we dropped L1521F and L673-7 because they are now known to have a faint embedded source from Spitzer’s observations (Bourke et al. 2006; Dunham et al. 2010). Column 5 provides the number of sources detected with both the line in Column 1 as the optically thick tracer and N2H+ as the optically thin tracer. Here, the sources detected in each set of observed lines are not exactly the same although most of the sources are commonly detected in those lines. Column 6 lists references from which the data are obtained—(1) Lee et al. 1999; (2) Lee et al. 2004; (3) Sohn et al. 2007; (4) LMT01.

Table 1
Data Summary

| Observing Line | Telescope   | Observing Mode | Number of Cores | Number of Cores | Reference |
|---------------|-------------|----------------|----------------|----------------|-----------|
| N2H\(^+\) 1–0 | Haystack 37 m | Single pointing | 72             | 72             | 1         |
| CS 2–1        | Haystack 37 m | Single pointing | 163            | 66             | 1         |
| CS 3–2        | NRAO 12 m    | Single pointing | 91             | 66             | 2         |
| HCN 1–0       | TRAO 14 m    | Single pointing | 65             | 48             | 3         |
| N2H\(^+\) 1–0 | FCRAO 14 m   | Mapping        | 35             | 35             | 4         |
| CS 2–1        | FCRAO 14 m   | Mapping        | 50             | 34             | 4         |

Notes.
Summary of the data used in this paper. Columns 1 and 2 list the observed molecular lines and the telescopes. Note that NRAO 12 m is now referred to as KP12 m, operated by Arizona Radio Observatory. Column 3 explains the survey modes that we used, single-pointing observations toward central regions of the cores and mapping observations fully covering the cores. The spectral line data that are used in this study have been obtained from several previous observations, single-pointing surveys of starless cores in CS 2–1 and N2H\(^+\) 1–0 (Lee et al. 1999), in CS 3–2 (Lee et al. 2004), and in HCN 1–0 (Sohn et al. 2007), mostly the same sources were detected in all four sets of molecular lines CS 2–1, 3–2, HCN 1–0, and N2H\(^+\) 1–0 except for a few sources. For example, the number of cores detected in the entire set of CS 2–1, 3–2 and N2H\(^+\) 1–0 is 64. Thus, two sources were detected in either CS 2–1 and N2H\(^+\) 1–0 only or CS 3–2 and N2H\(^+\) 1–0 only. Out of 48 sources detected in HCN 1–0 and N2H\(^+\) 46 cores were also detected in the set of CS and N2H\(^+\) lines. This indicates that starless cores detected in CS, HCN, and N2H\(^+\) that are discussed for various statistics from different molecular line observations in this paper are mostly the same.

The mapping survey of a total of 53 targets has been performed with CS 2–1 and/or N2H\(^+\) 1–0 to have 34 starless cores mapped in both lines (LMT01). These data are used in the analysis of the spectral asymmetry. The molecular line observations we collect for this study are summarized in Table 1. The cores studied here have properties of typical mean density of ~10\(^4\) cm\(^{-3}\) and column density of a few 10\(^21\) cm\(^{-2}\) (Lee & Myers 1999). The mapped radii of the cores in N2H\(^+\) lines vary from 0.1 to 0.3 pc with a typical value of ~0.1 pc. The cores traced in CS lines are more extended, sometimes twice more, than N2H\(^+\) cores. In Table 2 we collect detailed information on the starless cores that are frequently referred here, mostly from LMT01 regarding the degree of asymmetry in profiles and physical properties of the cores.

2. DATA

The spectral line data that are used in this study have been obtained from several previous observations, single-pointing surveys of starless cores in CS 2–1 and N2H\(^+\) 1–0 (Lee et al. 1999), in CS 3–2 (Lee et al. 2004), and in HCN 1–0 (Sohn et al. 2007), and a mapping survey in CS 2–1 and N2H\(^+\) 1–0 (LMT01). For these systematic surveys of starless cores we first constructed a catalog of optically selected cores (Lee & Myers 1999) from which 306 cores were selected as “starless” in the sense that they do not have either an embedded IRAS point source or a pre-main-sequence star.3

Next, we performed systematic spectral line surveys of 220 starless cores listed in the catalog in CS 2–1 and/or N2H\(^+\) 1–0 to sample 66 cores detected in both lines (Lee et al. 1999). Then we observed the cores in CS 3–2 to have 66 cores detected in both CS 3–2 and N2H\(^+\) (Lee et al. 2004), and also in HCN 1–0 to have 48 cores detected in both HCN and N2H\(^+\) (Sohn et al. 2007). Mostly the same sources were detected in all four sets of molecular lines CS 2–1, 3–2, HCN 1–0, and N2H\(^+\) 1–0 except for a few sources. For example, the number of cores detected in the entire set of CS 2–1, 3–2 and N2H\(^+\) 1–0 is 64. Thus, two sources were detected in either CS 2–1 and N2H\(^+\) 1–0 only or CS 3–2 and N2H\(^+\) 1–0 only. Out of 48 sources detected in HCN 1–0 and N2H\(^+\) 46 cores were also detected in the set of CS and N2H\(^+\) lines. This indicates that starless cores detected in CS, HCN, and N2H\(^+\) that are discussed for various statistics from different molecular line observations in this paper are mostly the same.

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3 Recent Spitzer’s Legacy Project “From Molecular Cores to Planet Forming Disks” (c2d; Evans et al. 2003) for small isolated cores indicated that about 20% of “starless” cores harbor a very faint Spitzer source which is called as Very Low Luminosity Objects (VeLLOs; Dunham et al. 2008). We dropped such cores in any number statistics in this paper.

3. ANALYSIS OF THE NORMALIZED VELOCITY DIFFERENCES ΔV OF SPECTRA

Quantifying properly the spectral asymmetry is very important to infer which internal motions are dominant in starless cores. The amount by which the optically thick spectrum is blueshifted or redshifted with respect to the optically thin line (N2H\(^+\) 1–0) can be estimated by using the normalized velocity difference \( \Delta V = (V_{\text{thick}} - V_{\text{thin}})/\Delta V_{\text{thin}} \), where \( V_{\text{thick}} \) and \( V_{\text{thin}} \) are the peak velocities of the optically thick and thin lines, and \( \Delta V_{\text{thin}} \) is the FWHM of the thin line (Mardones et al. 1997; Lee et al. 1999; LMT01). All the velocity information of the spectra was obtained with a Gaussian fit of the lines. This \( \Delta V \) is a useful quantity which can help determine the degree of spectral asymmetry. For example, if the \( \Delta V \) for the spectra is negative, this would indicate that the thick profile is in infall (or blue) asymmetry possibly tracing inward gaseous motions, called the blue
profile. On the other hand, if the $\delta V$ is positive, this may mean that the profile is now in outflow (or red) asymmetry tracing outward motions, called the red profile.

### 3.1. Number Distribution of $\delta V$ of Optically Thin and Thick Spectra

The number distribution of $\delta V$ of the observed spectra has been examined with single-pointing observations toward central regions of the cores using molecular lines of CS 2–1 (Lee et al. 1999), CS 3–2 (Lee et al. 2004), and HCN 1–0 (Sohn et al. 2007) as optically thick tracers and $N_2H^+$ 1–0 as an optically thin tracer. From the single-pointing survey of 220 starless cores in the CS 2–1 and/or $N_2H^+$ 1–0 lines, the $\delta V$ distribution has been constructed for 66 cores detected in both CS 2–1 and $N_2H^+$ 1–0 lines (Lee et al. 1999). The $\delta V$ distribution from single-pointing observations for CS 3–2 and $N_2H^+$ 1–0 has also been tested for 66 starless cores (Lee et al. 2004, hereafter LMP04).

Both $\delta V$ distributions for CS 2–1 and CS 3–2 with respect to $N_2H^+$ 1–0 are found to be significantly skewed to the negative value, suggesting that CS 2–1 and 3–2 lines preferentially trace inward motions in the cores (see Figure 3 of LMP04 for the revised $\delta V$ distributions). The $\delta V$ distribution for HCN 1–0 using its single-pointing observations showed that the degree of the skewness towards blue in the distribution (the negative value) is even greater than that for any other infall tracers such as CS 2–1 and 3–2, indicating that HCN is the best tracer of inward motions (Sohn et al. 2007). The skewed distribution of $\delta V$ to the blue for all tracers from previous single dish surveys implies that it is very likely that the central region of a core has inward gaseous motions.

How likely is it then for a core to show infall asymmetry at any place when one looks at the dense core? What kind of motions are more likely to be observed in a dense core? The $\delta V$ analysis using all mapping observations with the above infall conditions suggest that...
tracers may be able to address these questions. For this purpose we use CS 2–1 and N2H+ 1–0 mapping data for 34 starless cores by LMT01 which give the most extensive data set of the line spectra available for this δV analysis.

Figure 1(a) is a histogram for the number distribution of δV for all observed positions of 34 starless N2H+ cores, indicating an overabundance of blue profiles. Note that half of the sample (17 cores; the group A) has been selected as infall candidates based on the single-pointing observations of Lee et al. (1999), while the other half of the sample (the group B) has been selected because they were either bright in high-density tracers such as CS, N2H+, and NH3 lines, or very opaque in optical (LMT01). Figure 1(b) is the number distribution of δV for the cores for group A and Figure 1(c) is that for group B. These figures are intended to test whether the δV distribution of all cores shown in Figure 1(a) is significantly affected by a bias of sample selection. The mean value (and standard error of the mean, hereafter s.e.m.) of the δV distribution for the entire sample is −0.2 ± 0.02. The mean value of δV for the group of infall candidates in Figure 1(b) is −0.26 ± 0.02, while that for the no infall-biased sample of Figure 2(c) is −0.12 ± 0.03. This suggests that the δV distribution of the entire sample is somewhat affected by that of the infall candidates, group A. Nonetheless, it should be noted that the δV distribution of group B also exhibits a statistically significant overabundance of blue profiles.

In fact, the selection of our sample has been originally made from single-pointing observations toward 220 starless cores with high-density tracers such as CS and N2H+ among which 66 cores were both detected with two tracers. Thirty-four cores have been chosen for mapping with the same tracers on the basis of the brightness of the observed lines, especially the N2H+ line, to make follow-up mapping observations feasible, regardless of whether they are infall candidates or not. In this sense our sample is not biased in the selection of targets by the pre-existence of infall asymmetry in cores from the single-pointing survey, but by the brightness of the sources. Therefore the overabundance of blue profiles in the δV distribution should be affected by our selection bias toward bright (in N2H+) sources. What is really implied in the δV distribution of Figure 1 would be that bright N2H+ cores (i.e., cores with high column density) are likely to have inward gaseous motions. This result is further investigated in the following section.

3.2. Relation of the δV Distribution with Gas Column Density

This section suggests that regions of higher column density have a better chance of having more negative δV or being in inward gaseous motion. We use the integrated intensity of the N2H+ 1–0 line as the column density tracer. The N2H+ 1–0 line is usually optically thin, and the ion molecule N2H+ barely gets depleted in the dense core. Thus, N2H+ 1–0 is useful to trace the density distribution of the cores (e.g., Tafalla et al. 2004, 2006).

Figures 2 and 3 examine the dependence of δV on the integrated intensity of N2H+ using single-pointing data for CS 2–1, 3–2, HCN 1–0, and N2H+ from Lee et al. (1999, 2004) and Sohn et al. (2007). The data were selected if the integrated intensity of N2H+ is brighter than 5σ in the diagram. Note that all sources for which the integrated intensity of N2H+ is stronger than ~0.7 K km s\(^{-1}\) have negative δV except for L183 in HCN 1–0 F = 1–1.

**Figure 2.** δV\(_{\text{CS}}\) distribution for CS 2–1 and CS 3–2 vs. the integrated intensity of N2H+ for cores from the single-pointing survey of LMT99 and LMP04. The data for which the integrated intensity of N2H+ is brighter than 5σ are used in the diagram. Note that all sources for which the integrated intensity of N2H+ is stronger than ~0.6 K km s\(^{-1}\) have negative δV\(_{\text{CS}}\) except for L183.

**Figure 3.** δV\(_{\text{HCN}}\) distribution versus the integrated intensity of N2H+ for 39 cores from the single-pointing surveys of Sohn et al. (2007). The data for which the integrated intensity of N2H+ is brighter than ~5σ are used in the diagram. Note that all sources for which the integrated intensity of N2H+ is stronger than ~0.6 K km s\(^{-1}\) have negative δV\(_{\text{HCN}}\) except for L183.
average of the $\delta V$ values of all positions for each core where the integrated intensity of $N_2H^+$ is brighter than its $5\sigma$ uncertainty. The difference between Figures 4 and 5 is that Figure 4 displays the distribution of the $\delta V$ over all mapped positions, while Figure 5 shows the distribution of the average $\delta V$ over each core. Figure 5 indicates that the infall asymmetry of the CS line is more significant at a core with brighter peak intensity of $N_2H^+$.

Figures 4 and 5 show that denser regions have bluer spectra. In addition, such dense regions have a larger proportion of blue spectra, as shown in Figure 6. The fractional blue excess ($E$) given in the ordinate of Figure 6 is defined as $E = \frac{N(N_\mathrm{tot} - N_\nu)}{N_\mathrm{tot}}$, where $N_\nu$ is the number of positions with $\delta V_{CS} \leq -5\sigma_{CS}$, $N_\nu$ is the number of positions with $\delta V_{CS} \geq 5\sigma_{CS}$, $N_\mathrm{tot}$ is the total number of positions given by $N_\mathrm{tot} = N_\nu + N_\nu + N_0$, and $N_0$ is the number of positions with $-5\sigma_{CS} < \delta V_{CS} < 5\sigma_{CS}$. All the numbers regarding the excess are estimated with the data points in the 10 bins of the sample as in the case of Figure 4. The figure again shows that the positions where $N_2H^+$ is brighter tend to have higher blue excess and thus to have a more significant signature of inward motions. The $1\sigma$ uncertainty of the average in the $N_2H^+$ intensity is typically less than 0.01 K km s$^{-1}$ which is smaller than the size of the dots in the figure, except for that of the brightest data point, which is about 0.07 K km s$^{-1}$.

The uncertainty of $E$ is difficult to calculate from the noise of the spectra. However, we may estimate its approximate value by assuming that the typical $1\sigma$ uncertainty in $(N_\nu - N_\nu)$ is unity, corresponding approximately to one incorrect assignment in the sample of $N_\mathrm{tot} = 34$ in each bin. This implies, by the standard propagation of errors, that the uncertainty of $E$ of $\frac{1}{N_\nu} \approx 0.03$. This suggests that the uncertainty of $E$ is fairly small as in the case of the uncertainty of the $N_2H^+$ intensity. Thus, the apparent trend in Figure 6 is likely to be significant against uncertainties of the $N_2H^+$ intensity and of $E$.

3.3. Variation of $\delta V_{CS}$ with the Distance from the Peak Gas Column Density

This section examines how the asymmetric pattern of spectral lines changes with the distance from the density peak of a core.

We discuss this in Figure 7 where the $\delta V_{CS}$ of each spectrum is plotted against the distance of its position from the peak
intensity position of N$_2$H$^+$. The distances from us to the cores were adopted from Table 2 of Lee & Myers (1999). Figure 7(a) displays the $\delta V_{CS}$ distribution of the spectra of all sources where the integrated intensity of N$_2$H$^+$ is brighter than its 5$\sigma$ uncertainty, indicating that $\delta V_{CS}$ tends to be more negative at positions closer to the position of peak intensity. In the figure there is a break for this tendency at the radius of $\sim$0.1 pc, where the local mean value of $\delta V_{CS}$ is close to zero. Over 0.1 pc the $\delta V_{CS}$ becomes negative again, although it is less negative than at inner ($\sim$0.07 pc) positions, implying that blue profiles are also prevalent even at large radii. The break around $\sim$0.1 pc is mainly due to the contribution by the data from three cores, L183, L492-1, and L1495A-N, where both blue and red asymmetric CS profiles are seen in a comparable number. Red dots are the points of average values of $\delta V$s and N$_2$H$^+$ intensities for local positions as in the case of Figure 4.

Figure 7(b) is the same diagram as Figure 7(a), but without these cores, demonstrating that the mean value of $\delta V_{CS}$—close to zero in Figure 7(a)—is due to the distribution of blue and red profiles in a comparable number in three cores. L1512 is also another core showing such a distribution of spectra. But it has a relatively small number (nine) of data positions and most of its positions in the diagram are located within the radius of 0.06 pc from the N$_2$H$^+$ peak position. Thus, L1512 is not responsible for the break at $\sim$0.1 pc.

Figure 8 shows another display of the $\delta V_{CS}$ distribution with distance from the position of the peak N$_2$H$^+$ intensity using the fractional blue excess tool as in Figure 6. The figure shows that the fractional blue excess is more pronounced, implying an overabundance of blue profiles, in the inner region of the core (within a radius of about 0.07 pc from the column density peak of the core) than in its outer region. The 1$\sigma$ uncertainty of the average in the radial distance from the position of the peak N$_2$H$^+$ intensity is typically less than 0.003 pc which is smaller than the size of the dots in the figure, except for that of the most distant point, which is 0.017 pc. Because the uncertainty of $E$ is also expected to be fairly small as discussed in the last section, this trend seen in Figure 8 is expected to be significant.

As in the case of Figure 7, Figure 8(a) is a diagram for the spectra of all sources, showing that the blue excess is close to zero at $\sim$0.1 pc and becomes significant even at radii larger than 0.1 pc. Figure 8(b) is the same diagram as Figure 8(a), but without the above three cores, confirming that the break of the blue excess at $\sim$0.1 pc is due to these cores.

The foregoing figures show that most cores in our sample have spectral asymmetry maps indicating contracting motions. However, it is also clear that a minority of the cores cannot be described as primarily contracting. Therefore, we classify cores into four groups according to their apparent dynamical status. We then examine how $\delta V_{CS}$ varies with the distance from the core map peak within each group.

The classification of the cores was made by using two parameters given by LMT01. These are the fractional blue excess $E$ and the $P$-value of a Student $t$-test for the $\delta V_{CS}$ distribution for each core. The $P$-value is the probability of drawing our $\delta V_{CS}$ distribution from a zero mean $t$-distribution. The $E$ parameter determines how many blue or red profiles exist in a core, while the $P$ parameter informs us how the dominance of the blue or red profiles is significant in the core. These parameters are listed in Table 3 of LMT01. Here, the classification of the cores is given for 33 cores with $\delta V_{CS}$ measurement for more than three positions.

The first group of sources are the infall candidates suggested by LMT01 which show a significant overabundance of blue profiles in a core ($E \gtrsim 0.10$ and $P \lesssim 0.1$). This corresponds to groups 1 and 2 in Figure 6 of LMT01: L1355, L1498, L1495A-S, TMC2, L1544, TMC1, L1552, L1622A-2, L158, L183, L1689B, L234E-C, L234E-S, L492, L694-2, L1155C-2, L1155C-1, L981-1, and L1197. Here, we name these as candidates of “contracting core.”

The second group of sources are the cores where blue and red profiles are observed in a comparable number so that there is no significant blue or red excess ($E \approx 0$) with a large spread in the $\delta V_{CS}$ distribution (one standard deviation $\gtrsim 0.4$). This corresponds to group 5 in Figure 6 of LMT01: L1495A-N, L1507A, and L1512. We refer to this group to candidates as “oscillating core” because the mixture of blue and red profiles may be caused by oscillatory motions of gas as suggested by Lada et al. (2003), Redman et al. (2006), and Aguti et al. (2007).

The third group of sources is the cores dominated by red asymmetric profiles, showing significant overabundance of red profiles in a core ($E \lesssim -0.15$ and $P \approx 0.0$). This corresponds to group 3 in Figure 6 of LMT01: L134A, L429-1, and CB246. L134A was dropped from this group in LMT01 because it was erroneously treated as a source with a small number (< 7) of $\delta V_{CS}$ measurements, although it had nine positions where $\delta V_{CS}$ was obtained. Now we include L134A in this group. On the
other hand, L1521F, which had been classified in this group in LMT01, is dropped because it is now known to have an embedded source (Bourke et al. 2006). We refer to this group as the candidates of “expanding core.”

The fourth group of sources are the cores with blue or red excess and CS profile shapes similar to a single Gaussian form so that there is no significant blue or red excess ($E \approx 0$) with a small spread in the $\delta V_{CS}$ distribution (one standard deviation $\lesssim 0.3$). This corresponds to group 4 in Figure 6 of LMT01: L1333, L1495B, L1400A, CB23, L1517B, L1622A-1, L1696A, and L234E-N. Here, we included in this group CB23 which had been dropped from the classification of cores in LMT01 because of a small number (four) of measurements of $\delta V_{CS}$. We refer to this group as the candidates of “static core.”

Figure 9(a) displays the $\delta V_{CS}$ distribution versus the distance from the position of the N$_2$H$^+$ peak intensity for 19 contracting cores in group 1. In this group, there are more positions with negative $\delta V_{CS}$ than those with positive $\delta V_{CS}$ at every radius. Within $\sim 0.07$ pc this trend is much more significant: nearly all of the positions in contracting cores have negative $\delta V_{CS}$.

On the other hand, this trend is not seen in other groups of the cores. Figure 9(b) shows that the oscillating cores in group 2 have overall comparable positions at both positive and negative $\delta V_{CS}$ along the distance, although there are a few more positions with negative $\delta V_{CS}$ at the inner region $< 0.04$ pc and more positions with positive $\delta V_{CS}$ at the outer region $> 0.1$ pc. The expanding cores in group 3 show opposite distribution to that of contracting cores, i.e., much more positions with positive $\delta V_{CS}$ than those with negative $\delta V_{CS}$ (Figure 9(c)). The static cores in group 4 show no significant variation in the $\delta V_{CS}$ value along the distance from the peak N$_2$H$^+$ intensity, though with one exceptional position with the highest positive $\delta V_{CS}$ at the longest distance.

Note that the contracting cores are the majority of the data and their group shows similar $\delta V_{CS}$ distribution to what is found in Figures 7 and 8 for the entire sample of cores, while the other groups of cores do not show it. This suggests that the characteristic property of the predominant $\delta V_{CS}$ distribution of negative values along the radius of the cores comes from the $\delta V_{CS}$ distribution in the contracting cores.

4. DISCUSSION

4.1. Relation of the $\delta V$ Distribution with Gas Column Density and its Implication

In Section 3.2, we have shown that the bright N$_2$H$^+$ positions tend to have more negative $\delta V_{CS}$, a significant signature of inward motions. This section discusses this result in terms of individual cores and their dynamical status and interprets the discussion in terms of the evolution of the dense core.

Figure 10 indicates the distribution of $\delta V_{CS}$ against the integrated intensity of N$_2$H$^+$ for all available positions in the starless cores in four panels. While Figure 4 presents these data for all the cores in the plot, Figure 10 shows the same data in a separate plot for each core. Group (a) of Figure 10 displays the $\delta V_{CS}$ distribution against the integrated intensity of N$_2$H$^+$ for the contracting cores in decreasing order of $-\langle \delta V_{CS} \rangle$ showing that $\delta V_{CS}$ clearly tends to be more negative at the brighter positions of N$_2$H$^+$. On the other hand, the cores in the other groups do not show any trend with integrated intensity of N$_2$H$^+$ 1–0. The oscillating cores in group (b) show that the distribution of $\delta V_{CS}$ is polarized between positive and negative values of $\delta V_{CS}$, independent of the integrated intensity of N$_2$H$^+$. In the expanding cores in group (c), it is also hard to see any dependency of the distribution of $\delta V_{CS}$ on the integrated intensity of N$_2$H$^+$. Instead they have mostly positive $\delta V_{CS}$. The static cores in group (d) tend to be less bright in N$_2$H$^+$ emission than other types of the cores and show a uniform small spread of $\delta V_{CS}$ compared with that in oscillating cores.

Figure 11 is another presentation of the distribution of $\langle \delta V_{CS} \rangle$ as a function of the peak integrated intensity of N$_2$H$^+$ when the cores are combined into their four dynamical status groups. Figure 11(a) shows that contracting cores have the negative $\langle \delta V_{CS} \rangle$ distributed over a wide range of the peak integrated intensity of N$_2$H$^+$. On the other hand, the cores in other groups have the $\langle \delta V_{CS} \rangle$ distribution in a smaller range of the intensity of N$_2$H$^+$. The oscillating cores and the static cores are similarly distributed near the zero $\langle \delta V_{CS} \rangle$ value, but the oscillating cores have larger scatter (s.e.m. of 0.13–0.18) in the $\langle \delta V_{CS} \rangle$ value of each core because of the mixture of blue and red profiles in the core (Figure 11(b)), compared with that (s.e.m. $< 0.1$ mostly) in the $\langle \delta V_{CS} \rangle$ value of static cores (Figure 11(d)). All of the expanding cores have positive $\langle \delta V_{CS} \rangle$ contrary to the $\langle \delta V_{CS} \rangle$ distribution of contracting cores.

Figure 11 shows that brighter cores tend to be dominated by contracting cores as was also shown in Figure 6. In addition, Figure 11 shows that non-contracting cores tend to be similarly faint in each group, with $\int T_A^*$(N$_2$H$^+$)d$v \lesssim 1$ K km s$^{-1}$. Above a certain value ($\sim 1.6$ K km s$^{-1}$) of the integrated intensity of N$_2$H$^+$ there are contracting cores only (with negative $\langle \delta V_{CS} \rangle$). This suggests that as starless cores become denser and approach some specific column density, they tend to have more chances to contract. Above this critical value of column density all starless cores are always in inward motions. We derived such a critical
column density by using Equation (A4) of Caselli et al. (2002) and converted this to the corresponding H₂ column density of 6 × 10^{21} \text{ cm}^{-2} by using an average abundance of N₂H⁺ of ~6.8(±4.8) × 10^{-10} of starless cores which is obtained using Table 3 in Johnstone et al. (2010). Our diagram may indicate that there is a column density threshold value of ~6 × 10^{21} \text{ cm}^{-2} over which most starless cores are contracting. Note that this is very similar to the column density value of 8.0 × 10^{21} \text{ cm}^{-2} for star formation in dense cores suggested by Onishi et al. (2008).

Crapsi et al. (2005) have shown that N₂H⁺ column density [N(N₂H⁺)] can be an indicator of the evolutionary stage of starless cores since N(N₂H⁺) increases with other evolutionary indicators including N₂D⁺ column density [N(N₂D⁺)], N(N₂D⁺)/N(N₂H⁺), H₂ column density, and CO depletion factor. According to their investigation, it is likely that starless cores with higher N₂H⁺ column density are more evolved than the cores with lower N₂H⁺ column density. If this is true, Figure 11 may imply that, in terms of increasing column density, the starless cores in the four groups are in a sequence of core evolution.

In this picture, the static cores with the lowest column density may be in the earliest stage, the expanding cores or the oscillating cores in the next, and the contracting cores (with the highest column density) in the latest stage. We note that oscillating and expanding cores are nearly indistinguishable because of a small number of samples. It may be possible that some expanding cores are at the stage of outward motion in

Figure 10. $\delta V_{CS}$ distribution against the integrated intensity of N₂H⁺ for each starless core in four groups of cores in (a) contracting, (b) oscillating, (c) expanding, and (d) static motions. L234E-S to L183 belong to group (a), L1495A-N, L1507A, and L1512 belong to group (b), L134A, L429-1, and CB246 belong to group (c), and L1333 to L234E-N belong to group (d). In group (a) contracting cores are put in decreasing order of $-\langle \delta V_{CS} \rangle$. (A color version of this figure is available in the online journal.)
oscillatory mode. More samples of cores in each stage is needed to constrain the evolutionary sequence of the cores with better statistical significance.

The discussion for this evolutionary sequence is qualitatively similar to the picture discussed by Stahler & Yen (2010). Using perturbation theory, they showed that the starless core would undergo contraction if they are initially compressed or inflated by the oscillation. Our diagram of observing data seems to indicate a similar result. Once the static cores are perturbed, this may result in an imbalance between self-gravity and the outward pressure gradient, thus the expanding or oscillating motions in the core. Once a core becomes denser over the critical column density such as $6 \times 10^{17} \text{ cm}^{-2}$, it may be in “all” contracting motions. We note that there are also cores with low column density, but in inward motions, indicating that some cores may spend a very short time in oscillation or expansion.

The discussion for the timescale in each stage is also interesting. Lee & Myers (1999) have suggested that starless cores of a mean density of $(6-8) \times 10^{6} \text{ cm}^{-3}$ last for about $(0.3-1.6) \times 10^{6}$ years using the statistical number ratio $(\sim 3.26$ for the number ratio of starless cores and cores with embedded protostars) and the life time of the protostar as $(1-5) \times 10^{6}$ years. Ward-Thompson et al. (2007) re-estimated this life time of starless cores as $\sim 6 \times 10^{6}$ years using a better estimate of Class I life time $(\sim 2 \times 10^{5})$. This estimation also needs to be revised by considering that about 20% of the starless cores may not be “starless” because they contain an embedded very faint source, i.e., the VeLLO (Dunham et al. 2008), and the reference life time of protostars (Class 0 and I) has recently been updated to $0.54 \times 10^{6}$ years with much better statistics by Evans et al. (2009). By using these new information, our revised value of the life time of the detectable starless cores denser than $\sim 10^{4} \text{ cm}^{-3}$ is now estimated to be $\sim 1.4 \times 10^{6}$ years.

If starless cores share this duration for each evolutionary stage proportional to the statistics of the numbers in each class, the cores may spend $\sim 3 \times 10^{5} \times (\frac{6}{33} \times 1.4 \times 10^{6})$ years in the force balanced period, experience either expanding or oscillatory motions in the surface of the cores for $\sim 3 \times 10^{5} \times (\frac{6}{33} \times 1.4 \times 10^{6})$ years, and then contract for $\sim 8 \times 10^{5} \times (\frac{19}{33} \times 1.4 \times 10^{6})$ years.

Aguti et al. (2007) have calculated the modes of pulsation for an isothermal globule of gas in spherical shape for the core FeSt 1-457 and found its required mode as the least-damped mode of $l = 2$ with an oscillation period of $\sim 3 \times 10^{5}$ years. This oscillation period is consistent with our determination of the statistical period of starless cores in oscillation mode, even with small sample statistics.

4.2. Environmental Effect on Internal Motions in Starless Cores

Are internal motions in starless cores affected by the core environment? We examined the association of 35 $N_{2}H^{+}$ cores (including B68 and Fest1-457 as well as our sample) to any surrounding structures of clouds in the $A_{n}$ maps of the Digitized Sky Survey obtained using a star-count method by Dobashi et al. (2005), by checking how the core is enclosed with the lowest contour ($A_{n} = 0.5$) in the $A_{n}$ maps.

From this inspection by eye we found that among 35 $N_{2}H^{+}$ cores L694-2 is a core isolated entirely from nearby large complex complexes. There is also one small cloud where two of the cores, L134A and L183, are enclosed within the lowest contour ($A_{n} = 0.5$). This cloud is isolated from other nearby clouds. B68 is not identified in the $A_{n}$ map by Dobashi et al. (2005), probably because there are not enough background stars available toward B68 for enabling $A_{n}$ around the core to be estimated. From its location in the $A_{n}$ map, B68 seems located in a very small $A_{n}$ region within a surrounding cloud. Thus, we believe four sources (L694-2, L134A, L183, and B68) may be well isolated from large clouds.

On the other hand the majority of the cores (17 of 33 cores) are found to exist as a part of long filament clouds. They are L1333, L1498, L1498B, L1495A-N, L1495A-S, L1400A, TMC2, TMC1, L1507A, CB23, L1544, L1696A, L1689B, L158, L234E-N, L234E-C, and L234E-S. The rest of our sample (14 of 35 cores) are more likely surrounded by a large cloud or located on the edge of the cloud (L1355, L1517B, L1512, L1552, L1622A-2, L1622A-1, L492, L249-1, L1155C-2, L1155C-1 L981-1, L1063, L1197, CB246, and Fest1-457).

Can isolation of the cores from a large complex cloud affect its dynamical status? We may find some clues for the answer to this question if the isolated cores have their characteristic feature of spectral asymmetry. According to criteria given in Section 3.3, L694-2 and L183 are classified as contracting cores and L134A as an expanding core. B68 is known to have a mixture of blue and red profiles, interpreted as an indication of the oscillatory motions of gaseous material in the surface of a core (Redman et al. 2006; Lada et al. 2003). It is interesting to note that no core which is in isolation from other clouds has spectra of a Gaussian shape indicative of dynamically static status. However, we are cautious of drawing any conclusive remarks on the characteristic properties of the dynamical status of the isolated cores due to the poor statistics of our small sample; more data are needed.

Now we examine the difference in the dynamical status of starless cores in two other environments, the long filament clouds and the large complex clouds. According to previous classification criteria of the cores and examination of core
associations with large clouds, we find that nine contracting, two oscillating, and six static cores are located in the long filamentary clouds, while eight contracting, one oscillating, two expanding cores, and three static cores are in large complex clouds. Although there is a slight difference in the number of cores in two types of clouds, it seems hard to conclude whether the difference is significant or not, due to its limited statistics.

5. SUMMARY

This paper aims to discuss how likely it is for a starless core to be in either contracting, expanding, oscillating, or static motions and which conditions are related to the dynamical stage of the core, by analyzing asymmetric patterns in molecular lines. For this purpose we collected either single-pointing or mapped spectroscopic line data for several tens of starless cores and re-analyzed those especially by using the normalized velocity difference $\delta V_{\text{CS}}$ between optically thick and thin lines.

The main conclusions we found from this analysis are as follows.

1. Blue profiles are dominant in starless cores, implying that inward motions are prevalent in starless cores. These profiles are found to be more abundant and their asymmetry is blue at the positions of the core with stronger N$_2$H$^+$ or higher column density. This indicates that positions with high column density in the core are more likely contracting.

2. Relying on the distribution of their spectral asymmetric features, starless cores were classified to have four types of motions: contracting, oscillating, expanding, and static. More than half (19) of the 33 cores studied have spectral line maps dominated by evidence of contracting motions, about a quarter (8) of the cores show no significant evidence of either contraction or expansion, about 10% (3) of the cores are dominated by expanding motions, and about 10% (3) show a significant mixture of contracting and expanding motions, which may be interpreted as oscillatory motions.

3. Most of the contracting cores tend to have more positions with negative $\delta V_{\text{CS}}$ (blue asymmetry) than positive $\delta V_{\text{CS}}$ at every radius, with more concentration of negative $\delta V_{\text{CS}}$ within $\sim$0.07 pc from the peak N$_2$H$^+$ intensity region. This implies that inward motions in contracting cores are occurring along most lines of sight, with a predominance of those motions near the column density peak region of the cores.

4. Contracting cores are far more numerous for the bright cores. Above a certain peak column density ($\sim$6 $\times$ 10$^{21}$ cm$^{-2}$) only contracting cores are seen and no oscillating, expanding, or static cores are seen. This implies that as starless cores become denser, they are more likely to contract. Above some critical value of column density all starless cores are likely to be contracting.

5. In terms of increasing column density, starless cores in different internal motions may reflect their different stages of evolution: static cores in the earliest stage, expanding and/or oscillating cores in the next, and the contracting cores in the latest stage. This is consistent with the theoretical picture by Stahler & Yen (2010) where once a static core is perturbed, the core would show expanding or oscillatory motions, and would then begin prolonged contraction motions. On the other hand, we note that some starless cores have both low column density and inward motions. This may mean that these cores may not spend much time in oscillation or expansion.

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