HOW TO IDENTIFY PRE-PROTOSTELLAR CORES

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ABSTRACT

We have observed the HCO$^+$ $J = 3–2$ line toward 17 starless cores selected from the list of Ward-Thompson and coworkers. Six of these cores have line asymmetries indicative of collapse. The excess of blue-skewed profiles over red-skewed profiles is at least as large as that found in samples of Class 0 and early Class I sources. The observed line profiles have the same narrow line widths and small peak temperatures predicted for young sources in evolutionary models, but the blue/red ratios, like those of older sources, are higher than models predict. The infall signature also occurs over large scales, suggesting that these cores have overall inward motions. We have divided these starless cores into two groups based on the continuum photometry of Ward-Thompson and coworkers and our HCO$^+$ data. We find stronger HCO$^+$ emission among the cores detected in the submillimeter, and all the blue-skewed line profiles are in this group, supporting the suggestion of Ward-Thompson and coworkers that these are the preprotostellar cores.

Subject headings: ISM: clouds — stars: formation — submillimeter

1. INTRODUCTION

For years, the protostellar collapse stage had been an impenetrable mystery, until Walker et al. (1986) observed line profiles indicative of collapse in IRAS 16293$-$2422. Menten et al. (1987) disputed this interpretation and claimed that the asymmetric line profiles of Walker et al. were caused by rotation, but Zhou (1995) later modeled IRAS 16293$-$2422 as collapse with rotation. Zhou et al. (1993) observed B335, a slowly rotating source, and modeled its blue-peaked profiles as inside-out collapse (Shu 1977). André, Ward-Thompson, & Barsony (1993) extended the tripartite taxonomy of young stellar objects to include Class 0 objects (very embedded sources, such as B335 and IRAS 16293). André & Montmerle (1994) found that the Class 0 sources were more embedded than Class I sources and inferred that they had not yet accreted most of their mass. Spectral line surveys of Class 0 sources (Gregersen et al. 1997; Mardones et al. 1997) found nearly one-third to one-half of Class 0 objects displayed asymmetries in optically thick lines like those seen in B335 and IRAS 16293$-$2422.

However, the earliest phase of the collapse process, the transition between the quasi-static core formation and the beginning of infall onto a central object, is poorly understood. Beichman et al. (1986) examined the IRAS data for 95 cloud cores previously surveyed by Myers, Linke, & Benson (1983), Myers & Benson (1983), and Benson (1983) in $^{13}$CO, C$^{18}$O, and NH$_3$ and found that one-half had IRAS sources, which they deduced as arising from protostars. Ward-Thompson et al. (1994) observed 17 cores from Beichman et al. that have no IRAS sources. They detected 12 of these cores in the submillimeter and used maps to study the density profiles of five cores. Since these objects lacked IRAS sources, it is believed that protostars have not yet formed. From statistical arguments about the lifetimes of these cores and the fact that the observed density profiles are similar to those predicted by ambipolar diffusion models, Ward-Thompson et al. identified these starless cores as in the ambipolar diffusion phase and preprotostellar. This stage precedes the Class 0 phase and is sometimes referred to as the pre-protostellar core stage.

We observed the objects surveyed by Ward-Thompson et al. using the HCO$^+$ $J = 3–2$ line, a line that readily displays an asymmetry indicative of protostellar collapse, to see whether an early collapse phase could be found. Lee, Myers, & Tafalla (1999) have completed a similar survey using CS and N$_2$H$^+$ lines.

2. OBSERVATIONS AND RESULTS

We observed the 17 starless cores listed in Table 1 in the HCO$^+$ $J = 3–2$ line with the 10.4 m telescope of the Caltech Submillimeter Observatory (CSO)$^3$ at Mauna Kea, Hawaii in 1995 March, 1995 December, 1996 June, 1998 July, 1998 December, and 1999 July. We used an SIS receiver (Kooi et al. 1992) with an acousto-optic spectrometer with 1024 channels and a bandwidth of 49.5 MHz as the back end. The frequency resolution ranged from slightly less than 3 channels, 0.15 km s$^{-1}$ at 267 GHz, for the 1995 observations to closer to 2 channels, 0.12 km s$^{-1}$ at 267 GHz, for the 1998 observations. The antenna temperature, $T_A^*$, was obtained from chopper wheel calibration. Information about the observed lines is listed in Table 2. Planets were used as calibration sources for calculating the main-beam efficiency. Data from separate runs were resampled to the resolution of the run with the worst frequency resolution before averaging. A linear baseline was removed before scans were averaged.

Line properties are listed in Table 3. For lines without two clearly distinguished peaks, $T_A^*$, the peak temperature,
### TABLE 1
**List of Sources**

| Name      | R.A. (1950.0) | Decl. (1950.0) | Off Positiona (arcsec) | Distance (pc) | 450 μm (mJy) | 800 μm (mJy) | 1.1 mm (mJy) | 1.3 mm (mJy) |
|-----------|---------------|----------------|------------------------|---------------|--------------|--------------|--------------|--------------|
| L1498     | 04 07 50.0    | 25 02 31       | (−1200, 0)             | 140           | 700 ± 80     | 120 ± 18     | 35 ± 6       | 10 ± 2.5     |
| L1495D    | 04 11 15.5    | 28 07 20       | (−900, 0)              | 140           | ...          | <135         | <44          | <30          |
| L1506     | 04 15 30.3    | 25 13 22       | (−900, 0)              | 140           | ...          | <66          | <48          | ...          |
| L1521A    | 04 23 38.4    | 26 09 27       | (−900, 0)              | 140           | ...          | <110         | <80          | ...          |
| L1517C    | 04 51 35.9    | 30 30 00       | (−900, 0)              | 140           | 836 ± 160    | 100 ± 30     | <83          | <7.5         |
| L1517A    | 04 51 54.8    | 30 28 53       | (−900, 0)              | 140           | 1280 ± 330   | 105 ± 18     | <60          | <5.4         |
| L1517D    | 04 52 36.5    | 30 34 02       | (−900, 0)              | 140           | <4500        | <120         | <130         | ...          |
| L1512     | 05 00 54.4    | 32 39 37       | (−900, 0)              | 140           | <6000        | 107 ± 21     | 45 ± 9       | <16          |
| L1544     | 05 01 13.1    | 25 06 56       | (−900, 0)              | 140           | 1300 ± 240   | 450 ± 58     | 193 ± 30     | 46 ± 4        |
| L1582A    | 05 29 14.6    | 12 28 08       | (−900, 0)              | 140           | <1240        | 160 ± 27     | <54          | <30          |
| L134A     | 15 51 05.6    | −04 26 10      | (−900, 0)              | 150           | <60          | <60          | <163         |              |
| L183      | 15 51 32.7    | −02 42 19      | (600, 0)               | 150           | <1500        | 269 ± 30     | 108 ± 26     | <134         |
| L1696A    | 16 25 30.0    | −24 13 22      | (0, −1200)             | 125           | 800 ± 160    | 105 ± 18     | 62 ± 12      | <58          |
| L1689A    | 16 29 10.5    | −24 57 22      | (0, −900)              | 125           | 2200 ± 300   | 290 ± 45     | <102         | 54 ± 15      |
| L1689B    | 16 31 47.0    | −24 31 45      | (0, −900)              | 125           | <3000        | 362 ± 40     | 140 ± 34     | 134 ± 11     |
| L63       | 16 47 19.4    | −18 01 16      | (0, −900)              | 125           | 1600 ± 200   | 367 ± 23     | <93          | <96          |
| B133      | 19 03 27.3    | −06 57 00      | (0, −600)              | 400           | <1800        | 341 ± 63     | <120         | <56          |

Note.—Units of right ascension are hours, minutes, and seconds, and units of declination are degrees, arcminutes, and arcseconds.

*a* The off position used for position switching.

*b* All photometry from Ward-Thompson et al. 1994.

### TABLE 2
**List of Observed Lines**

| Molecule | Transition | Beam Width (arcsec) | Resolution (km s⁻¹) | Frequency (MHz) |
|----------|------------|---------------------|---------------------|-----------------|
| H¹³CO⁺   | J = 3–2   | 26                  | 0.66                | 0.16            |
| HCO⁺     | J = 3–2   | 26                  | 0.66                | 0.16            |

### TABLE 3
**Results**

| Source   | Line       | $T^*_S$ (K) | $V_{LSR}$ (km s⁻¹) | $ΔV$ (km s⁻¹) |
|----------|------------|-------------|--------------------|---------------|
| L1498    | HCO⁺ J = 3–2 | 0.48 ± 0.04 | 7.81 ± 0.02        | 0.51 ± 0.04   |
| L1495D   | HCO⁺ J = 3–2 | <0.05       | ...                | ...           |
| L1506    | HCO⁺ J = 3–2 | 0.20 ± 0.03 | 7.47 ± 0.02        | 0.38 ± 0.07   |
| L1521A   | HCO⁺ J = 3–2 | <0.05       | ...                | ...           |
| L1517C   | HCO⁺ J = 3–2 | 0.21 ± 0.05 | 5.63 ± 0.03        | 0.28 ± 0.09   |
| L1517A   | HCO⁺ J = 3–2 | 0.26 ± 0.05 | 5.72 ± 0.04        | 0.70 ± 0.10   |
| L1517D   | HCO⁺ J = 3–2 | <0.05       | ...                | ...           |
| L1512    | HCO⁺ J = 3–2 | 0.41 ± 0.04 | 7.05 ± 0.02        | 0.45 ± 0.04   |
| L1544    | H¹³CO⁺ J = 3–2 | 0.09 ± 0.02 | 7.18 ± 0.04        | 0.50 ± 0.10   |
| L1582A   | HCO⁺ J = 3–2 | 1.11 ± 0.07 | 6.96 ± 0.06        | 0.60 ± 0.12   |
| L134A    | HCO⁺ J = 3–2 | 0.91 ± 0.07 | 7.44 ± 0.06        | ...           |
| L183     | H¹³CO⁺ J = 3–2 | 0.77 ± 0.03 | 10.06 ± 0.02       | 0.83 ± 0.04   |
| L1689A   | H¹³CO⁺ J = 3–2 | 0.23 ± 0.04 | 2.93 ± 0.04        | 0.44 ± 0.11   |
| L1696A   | HCO⁺ J = 3–2 | 0.28 ± 0.01 | 2.27 ± 0.08        | 0.96 ± 0.16   |
| B133     | H¹³CO⁺ J = 3–2 | 0.12 ± 0.03 | 12.27 ± 0.04       | 0.38 ± 0.07   |
| L1689B   | H¹³CO⁺ J = 3–2 | <0.03       | ...                | ...           |
We observed 17 sources in this survey. All of the sources were observed in the HCO\(^+\) \(J = 3-2\) line. Six sources were also observed in the H\(^{13}\)CO\(^+\) \(J = 3-2\) line. Six sources showed a blue asymmetry in the HCO\(^+\) \(J = 3-2\) line (Fig. 1). Eight sources showed symmetric lines (Fig. 2), and three sources were not detected. The spectra in Figures 1 and 2 are from the central position except that of L1689B, which is from \((-15^\circ, 15^\circ)\), which we chose because it was the strongest position.

3. **INDIVIDUAL SOURCES**

3.1. **L1498**

Wang (1994) observed absorption in the H\(_2\)CO 6 cm line against the cosmic microwave background radiation similar to that observed in B335. Kuiper, Langer, & Velusamy (1996) posited that this core was quasi-static or slowly contracting and that the outer envelope was growing. They also concluded that this core could collapse within the next \(5 \times 10^6\) yr. Wolkovitch et al. (1997) determined that this core was extremely quiescent based on its narrow CCS line widths. The HCO\(^+\) \(J = 3-2\) line (Fig. 2) shows no asymmetry and is at the same velocity as the N\(_2\)H\(^+\) and C\(_3\)H\(_2\) lines observed by Benson, Caselli, & Myers (1998).

3.2. **L1506**

The HCO\(^+\) \(J = 3-2\) spectrum (Fig. 2) shows one component at 7.5 km s\(^{-1}\) with a possible second component at 9 km s\(^{-1}\).

3.3. **L1517C**

The HCO\(^+\) \(J = 3-2\) line (Fig. 2) is too weak to detect an asymmetry.

3.4. **L1517A**

We observe a slight blue shoulder in HCO\(^+\) \(J = 3-2\) (Fig. 2).

3.5. **L1512**

Caselli, Myers, & Thaddeus (1995) observed the hyperfine components of the N\(_2\)H\(^+\) \(J = 1-0\) line and found that a single excitation temperature could not fit the spectra, an anomaly usually seen in starless cores. The HCO\(^+\) \(J = 3-2\) line (Fig. 2) is symmetric and is at the same velocity as the N\(_2\)H\(^+\) and C\(_3\)H\(_2\) lines (Benson et al. 1998).

3.6. **L1544**

Myers et al. (1996) modeled the H\(_2\)CO \(J = 2_{12}-1_{11}\) line as arising from infall. Tafalla et al. (1998) found that their CS \(J = 2-1\) observations could be modeled as arising from inward motions, but those inward motions are not consistent with the predictions of the Shu (1977) inside-out collapse model. Williams et al. (1999) observed similar infall speeds in N\(_2\)H\(^+\) \(J = 1-0\) on scales of 10" to those observed by Tafalla et al. Ohashi et al. (1999) mapped this core in CCS \(J_N = 3_{2}-2_{1}\) and observed both infall and rotational motion. Ciolek & Basu (2000) have modeled the observations of Tafalla et al. and Williams et al. in the context of ambipolar diffusion. The HCO\(^+\) \(J = 3-2\) spectrum is blue-peaked with the H\(^{13}\)CO\(^+\) \(J = 3-2\) line peaking in the dip (Fig. 1). The N\(_2\)H\(^+\) peaks between the H\(^{13}\)CO\(^+\) line and the HCO\(^+\) peak, while the C\(_3\)H\(_2\) peaks on the H\(^{13}\)CO\(^+\) line (Benson et al. 1998).
3.7. L1582A

The HCO$^+$ $J = 3–2$ line is symmetric (Fig. 2). The N$_2$H$^+$ line of Benson et al. has the same peak velocity as the HCO$^+$ line. There is a hint of a blueshift relative to the N$_2$H$^+$ velocity but not enough to warrant inclusion as an infall candidate.

3.8. L134A

The HCO$^+$ $J = 3–2$ spectra displays a symmetric line (Fig. 2). The N$_2$H$^+$ and C$_2$H$_2$ lines (Benson et al. 1998) peak at the blue edge of our HCO$^+$ line. Because those lines were observed 115° from our position, we disregard this source in the statistical discussion in §4.2.

3.9. L183

Fulkerson & Clark (1984) used the H$_2$CO 6 cm line to model the density distribution as an inverse square law. The CS $J = 2–1$ line observed by Snell, Langer, & Frerking (1982) is similar in velocity and shape to our HCO$^+$ $J = 3–2$ spectra (Fig. 1). The HCO$^+$ $J = 3–2$ line is self-absorbed with the blue peak slightly stronger. The H$^{13}$CO$^+$, N$_2$H$^+$, and C$_2$H$_2$ lines (Benson et al. 1998) peak in the self-absorption dip.

3.10. L1696A

The HCO$^+$ $J = 3–2$ line is symmetric with a faint blue shoulder (Fig. 2). The peak velocity corresponds to that of the optically thin lines of Benson et al.

3.11. L1689A

We observe a broad, blue-skewed line in HCO$^+$ $J = 3–2$ (Fig. 1).

3.12. L1689B

The spectra for the HCO$^+$ $J = 3–2$ line is blue skewed with the H$^{13}$CO$^+$ $J = 3–2$ line peaking to the red of the peak velocity of the HCO$^+$ line (Fig. 1).

3.13. L63

The HCO$^+$ $J = 3–2$ line is strongly blue skewed, and the H$^{13}$CO$^+$ line peaks in the middle of the HCO$^+$ line (Fig. 1). The N$_2$H$^+$ and C$_2$H$_2$ lines (Benson et al. 1998) are at the velocity of the red edge of the blue peak.

3.14. B133

Hong et al. (1991) have mapped this core in $^{12}$CO and $^{13}$CO $J = 1–0$. The HCO$^+$ $J = 3–2$ line is slightly blue skewed (Fig. 1). The N$_2$H$^+$ and C$_2$H$_2$ lines of Benson et al. peak at the red edge of the blue peak.

3.15. Nondetections

The HCO$^+$ $J = 3–2$ line was not detected down to a limit of 0.05 K in L1495D, L1521A, and L1517D.

4. ANALYSIS

4.1. New Collapse Candidates in HCO$^+$

Six of these cores, L1544, L1689A, L1689B, L183, L63, and B133, have line profiles with blue asymmetry. A blue asymmetry in an optically thick line such as HCO$^+$ $J = 3–2$ can be caused by protostellar collapse (Leung & Brown 1977; Zhou & Evans 1994). We observed H$^{13}$CO$^+$ $J = 3–2$ in all of these sources to find the rest velocity, and we also used the N$_2$H$^+$ and C$_3$H$_2$ observations of Benson et al. to provide optically thin line velocities. If optically thin lines have the same velocity as the dip of the double-peaked line, the dip is self-absorption from the ambient cloud and not caused by two separate velocity components blended together.

For such narrow lines as seen in these sources, the rest frequencies of lines become an issue. The frequency of the HCO$^+$ $J = 3–2$ line is known to within an uncertainty of 0.01 MHz, but the uncertainty of the H$^{13}$CO$^+$ $J = 3–2$ is potentially large. The standard value in the JPL data base (Pickett et al. 1998) is 260.255478 GHz. It is calculated from measurements of the two lower lines (Woods et al. 1981; Bogey, Demuyck, & Destombes 1981), making it impossible to estimate uncertainties in the $J = 3–2$ line frequency. Comparing the velocities of sources done in H$^{13}$CO$^+$ here and elsewhere (Gregersen et al. 1997, 2000) with line velocities of the same sources in N$_2$H$^+$, on average the H$^{13}$CO$^+$ line is 0.16 ± 0.04 km s$^{-1}$ to the red of the N$_2$H$^+$ line. Since it is unlikely that the H$^{13}$CO$^+$ would be consistently red-shifted from the N$_2$H$^+$, we have shifted our H$^{13}$CO$^+$ spectra by 0.16 km s$^{-1}$ to the blue and propose a frequency of 260.255617 ± 0.000035 GHz for the H$^{13}$CO$^+$ $J = 3–2$ line, 0.139 MHz higher than the standard value.

For four of these sources, L1544, B133, L183, and L1689B, the H$^{13}$CO$^+$ line does peak in the self-absorption dip, one of the conditions that must be met before a core can be called a candidate for protostellar collapse. In L63, the H$^{13}$CO$^+$ coincides with the dip but the N$_2$H$^+$ lies between the dip and the red peak. We did not detect H$^{13}$CO$^+$ in L1689A, so we cannot make a claim about its quality as a collapse candidate.

How do the conclusions from HCO$^+$ compare to those of Lee et al. (1999), who observed CS and N$_2$H$^+$? They did not observe B133 or L1689A, but they found L1544, L1689B, and L183 (their position for L183B is closest to the core we call L183) to be infall candidates. There are slight differences between the CS and HCO$^+$ spectra. L1689B has a blue peak with a red shoulder in HCO$^+$ and double-peaked profile with a strong blue peak in CS. L1544 has a strong blue peak in HCO$^+$ but two peaks of equal strength in CS. L183 has similarly shaped spectra in both lines. Lee et al. (1999) observed a red peaked profile in L63, but their position differs substantially from ours. In general, the different tracers agree reasonably well.

4.2. Line Profile Statistics

Optically thick lines in collapsing sources show a double-peaked line profile with the blue peak stronger than the red peak. There are two ways of quantifying the asymmetry of the line. One could use the ratio of the strengths of the two peaks or the asymmetry parameter (Mardones et al. 1997), $$\delta V = (V_{\text{thick}} - V_{\text{thin}}) \Delta \text{thin}$$ where $V_{\text{thick}}$ is the velocity of the peak of the optically thick line, $V_{\text{thin}}$ is that of the optically thin line, and $\Delta \text{thin}$ is the line width of the optically thin line. We list the results in Table 4. We do not list the results for all the objects where HCO$^+$ was observed but only those objects for which we were able to establish a rest velocity from H$^{13}$CO$^+$, N$_2$H$^+$, or C$_3$H$_2$. L134A is listed in parentheses because its N$_2$H$^+$ spectrum was observed 115° from our HCO$^+$ spectrum. All the other sources for which we used the N$_2$H$^+$ line to determine the asymmetry were

4 http://spec.jpl.nasa.gov.
observed within 40° of our HCO⁺ position. In Table 5, we list the number of blue, symmetric, and red sources as determined by the asymmetry parameter and visual inspection of the line profiles. Following the classification of Mardones et al., sources with asymmetry less than −0.25 are blue while those with asymmetry greater than 0.25 are red. The excess, which characterizes how blue a sample of objects is, is the number of blue sources minus the number of red sources divided by the total number of sources. The excess as determined from the asymmetry parameter leaving aside L134A is 0.66, higher than those derived for samples of Class 0 and I sources, 0.25 and 0.39, respectively, using the HCO⁺ J = 3–2 line (Gregersen et al. 2000). Because the number of sources in our sample is small, it is unclear whether the larger excess is significant, but it appears to be at least as large as in the later stages. Lee et al. found the mean δV of starless cores to be −0.24 ± 0.04, not so different from the mean δV for Class 0 sources, −0.28 ± 0.10 (Mardones et al. 1997). For the HCO⁺ observations of all three categories, the mean δV using the H¹³CO⁺ J = 3–2 line frequency proposed in the previous section are −0.34 ± 0.13, −0.11 ± 0.09, and −0.17 ± 0.08 for starless cores, Class 0, and Class I objects, respectively. Thus, on the basis of line asymmetries, these starless cores cannot be distinguished from an older, protostellar population.

4.3. Are These Young Sources?

Zhou (1992) modeled CS lines in cores that have not yet formed a protostar but are evolving toward the singular isothermal sphere, the starting point of the Shu (1977) collapse model. He found CS lines with no asymmetry, narrow line widths that increased after collapse began, and peak line temperatures that increased until collapse began. Gregersen et al. (1997) did evolutionary models of HCO⁺ J = 3–2 in collapsing clouds and found that such line parameters as peak temperature, line width, and blue-red asymmetry increase with time to a maximum value and then decline. Therefore, if we observed sources that were just beginning to collapse, these sources would have HCO⁺ J = 3–2 lines that have slight asymmetry, small peak temperatures, and narrow line widths. If we extend these results backward to t = 0, to the beginning of collapse, we should expect similar line parameters to those of Zhou (1992). Also, since the luminosity of the protostar does not rise immediately, there is some time after collapse begins but before a source would have been detected by IRAS, so the early stages of the evolutionary models of Gregersen et al. could be applied to “pre-protostellar” objects. In these models, important processes such as cloud chemistry and protostellar heating that increase the line width and peak temperatures are glossed over or simplified, so the resulting evolutionary “tracks” are best seen as rough sketches of line parameter evolution. In Figure 3, we plot peak temperature and line width versus the blue-red ratio for the two abundance distributions modeled in Gregersen et al. The evolutionary “tracks” in both panels go roughly from the lower left corner to the upper right. We see that the starless cores are congested toward the lower (i.e., “younger”) half of the panel and the Class 0 and I sources that have IRAS sources extend farther to the upper ends of the two panels.

However, there are indications that some of these sources have already begun to collapse in a different way than the

| Method     | Blue | Symmetric | Red  | Excess |
|------------|------|-----------|------|--------|
| Asymmetry  | 6    | 3         | 0    | 0.67   |
| Profiles   | 6    | 8         | 0    | 0.43   |

![Fig. 3](image-url)
Shu model predicts. Several of the starless cores have blue/red ratios that are too large for early collapse and more like the extreme blue-red ratios seen in more evolved Class 0 sources. In fact, B133 displays the most extreme ratio between the blue and red peaks of any source in any class. The blue-red ratios for this and other sources are too high to arise in a Shu model. Mardones (1998) modeled several alternative velocity fields and found that a model in which the entire cloud collapses produces the highest blue-red ratio. These large blue-red ratios are further discussed in the next section.

4.4. Extended Infall Signatures

We have partially mapped five cores that showed asymmetric line profiles to observe the extent of the asymmetry. The blue-skewed profiles typically stretch over a large area for such young cores. For example, in L1689B (Fig. 4), the self-absorption, or blue-skewed lines, stretches over roughly 0.04 × 0.03 pc. There are some red profiles in the southeast area of the map. For L63 (Fig. 5), the blue skewness is seen in an area 0.07 × 0.03 pc. We show these two cores because these are the largest maps we have done with good signal-to-noise ratio. Tafalla et al. (1998) have commented on this large extent of the infall signature in L1544 (map in Fig. 6). They showed that if L1544 were undergoing inside-out collapse, it would have produced a protostar easily visible to IRAS and that such an early, large-scale infall does not fit with most theories of protostellar collapse.

These observations of extended infall signatures in HCO\(^+\) combined with the extreme blue-red ratios mentioned in the last section strengthen the case for extended inward motions. Myers & Lazarian (1998) have proposed that turbulent dissipation in a cloud produces an overall implosion starting from the core exterior as an explanation for extended infall signatures. Alternatively, Li (1999) has found evidence for extended inward motions at speeds up to one-half the sound speed in calculations of core formation in weakly magnetized clouds. Similar speeds also appear in the model of Ciolek & Basu (2000).

4.5. Starless or Pre-protostellar?

The question of whether to call these cores starless or pre-protostellar is a thorny one. While these cores have no IRAS sources and so can all be called starless, the term pre-protostellar implies that the future evolution of these objects can be definitely predicted. However, we can use the submillimeter observations of Ward-Thompson et al. (1994)
to divide the sample into those cores detected by Ward-Thompson et al. at one or more wavelengths and those not detected at all (Table 6). Of the 12 cores in the first group, six display blue asymmetry while the other six have no asymmetry. The six cores that display blue asymmetry are the strongest in the submillimeter continuum. Of the five cores Ward-Thompson et al. did not detect, two have symmetric profiles while we did not detect the other three in HCO\(^+\). The two detections of these cores were among the weakest lines observed. We also include the NH\(_3\) observations of Benson & Myers (1989) as a marker of dense core evolution. Of the 12 cores with submillimeter emission, all were observed in NH\(_3\). Of the five others, only one was observed. Five of the cores in the first group have since been mapped in the submillimeter continuum (Shirley et al. 2000). The four most centrally condensed cores show blue asymmetry. The least centrally condensed core, L1512, has no asymmetry in HCO\(^+\).

There is a clear distinction between those cores with submillimeter continuum and those without. The first group has stronger line emission that often shows what could be the beginning of infall. The group with relatively strong submillimeter continuum, HCO\(^+\), and NH\(_3\) emission are the likeliest to be pre-protostellar in nature, consistent with the suggestion by Ward-Thompson et al. (1994). The cores with weak submillimeter continuum could eventually form stars but were undetected simply because of lower column density. These cores may be in an even earlier evolution stage in which cores are just beginning to form, or these cores may be forming stars of lower mass. If these cores are weakly centrally concentrated, they would not have a sufficient excitation temperature gradient for infall asymmetry. Further observations would be needed to resolve the nature of these objects.

### 5. CONCLUSIONS

We have observed 17 starless cores in HCO\(^+\) \(J = 3\rightarrow 2\) in search of the spectral signature of pre-protostellar collapse. These objects do seem to be a younger population than the Class 0 sources based on their narrow line widths and weak peak temperatures. We have observed blue asymmetric line profiles in six of these cores, and we suggest L1544, L1689B, B133, and L183 as good protostellar collapse candidates and L1689A and L63 as worthy of further observations in the H\(^{13}\)CO\(^+\) \(J = 3\rightarrow 2\) line. The blue excess of this sample is as prominent as in samples of older Class 0 and 1 sources, suggesting that infalling protostars are not exclusively to be found among the Class 0 sources. A population of likely pre-protostellar cores can be distinguished by their strong submillimeter continuum and HCO\(^+\) and NH\(_3\) spectral line emission.

However, recently Tafalla et al. (1998) have found that L1544 cannot be described as inside-out collapse. If infall is happening in that core, it cannot be explained by any current infall model, suggesting that further study of these cores can tell us about the very beginning of the collapse process.

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### TABLE 6

| Source Continuum | HCO\(^+\) | NH\(_3\) | Blue Profile |
|------------------|----------|---------|-------------|
| L1498             | Y        | Y       | Y           |
| L1517C            | Y        | Y       | Y           |
| L1517A            | Y        | Y       | Y           |
| L1512             | Y        | Y       | Y           |
| L1544             | Y        | Y       | Y           |
| L1582A            | Y        | Y       | Y           |
| L183              | Y        | Y       | Y           |
| L1696A            | Y        | Y       | Y           |
| L1689A            | Y        | Y       | Y           |
| L1689B            | Y        | Y       | Y           |
| L63               | Y        | Y       | Y           |
| B133              | Y        | Y       | Y           |
| L1495D            | N        | N       | N           |
| L1506             | N        | N       | N           |
| L1521A            | N        | N       | N           |
| L1517D            | N        | N       | N           |
| L134A             | N        | Y       | Y           |

The cores with weak submillimeter continuum could eventually form stars but were undetected simply because of lower column density. These cores may be in an even earlier evolution stage in which cores are just beginning to form, or these cores may be forming stars of lower mass. If these cores are weakly centrally concentrated, they would not have a sufficient excitation temperature gradient for infall asymmetry. Further observations would be needed to resolve the nature of these objects.
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