DENSE CORES IN DARK CLOUDS. XI. A SURVEY FOR N₂H⁺, C₃H₂, AND CCS

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ABSTRACT

We have used the 3 mm receiver and upgraded antenna of Haystack Observatory to make high spatial and spectral resolution observations of lines of N_2H^+ and C_3H_2 in 60 dense cores. Both species are detected in most of the cores, and the velocities, and line widths are well correlated. This suggests that ions and neutrals are well coupled. We found $v_{D,max} \leq 0.03$ km s⁻¹, which is the first observational constraint on the relative speed of ions and neutrals in star-forming dense cores. Twenty of the cores were also observed in the $J_N = 4_3-3_2$ line of CCS. From our N_2H^+ observations, the fractional abundance of the molecular nitrogen N_2 is found to be $\simeq 7 \times 10^{-5}$, consistent with all the nitrogen being in molecular form and not depleted onto dust grains.

Subject headings: ISM: clouds — ISM: molecules — line: profiles — radio lines: ISM

1. INTRODUCTION

Systematic surveys of regions of high extinction in nearby dark clouds have shown that these "dense cores" play an important role in star formation (Beichman et al. 1986; Benson & Myers 1989, hereafter BM). To further study the physical and chemical properties of dense cores, observations are needed that can resolve the structure of cores, in lines sensitive to gas density $n > 1 \times 10^4$ cm⁻³. This paper describes surveys of dense cores in such lines of N₂H⁺, C₃H₂, and CCS. In a later paper we present mapping studies of the structure of a large sample of cores in the J = 1-0 line of N₂H⁺ (Caselli et al. 1998a).

Because Haystack Observatory³ has recently completed an upgrade of the 37 m telescope to enable operation at 3 mm (Barvainis et al. 1994), we have pursued higher resolution extensions of the BM NH_3 line survey to study the relative motions, abundances, and structure in low-mass dense cores in dark clouds.

Surveys of N_2H^+ , C_3H_2 , and CCS have already been performed in Galactic molecular clouds. However, and in particular for N_2H^+ , precedent surveys were carried out with lower spatial and spectral resolution than is now possible. In addition, this is the first survey we know of that compares both ionic and neutral species with high spatial and spectral resolution at the same positions. In § 2 we review the main studies of the three molecular species. Observational details are given in § 3. Results are presented in § 4 and discussed in § 5. In § 6 we summarize the main conclusions of this work.

2. PREVIOUS N_2H^+ , C_3H_2 , and CCS surveys

2.1. N_2H^+

The $J = 1 \rightarrow 0$ rotational transition of diazenylium (N_2H^+) has been (1) first discovered by Turner (1974) in the direction of massive star-forming regions as an unidentified triplet of lines at 93 GHz, (2) tentatively identified by Green,

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Montgomery, & Thaddeus (1974), and (3) confirmed by Thaddeus & Turner (1975), who resolved the predicted hyperfine structure of the inner nitrogen nucleus.

The first survey of $N_2H^+(1-0)$ in well-known sites of massive star-forming regions was carried out by Turner & Thaddeus (1977). After this study, N_2H^+ and its isotopes $(N_2D^+, H^{15}NN^+, and HN^{15}N^+)$ were observed toward a few dark clouds, such as L134N and TMC-1 (Snyder et al. 1977; Turner & Zuckerman 1978; Swade 1989). Womack, Ziurys, & Wyckoff (1992a) made an extensive survey of the $J = 1 \rightarrow 0$ and $J = 3 \rightarrow 2$ lines of N_2H^+ in star-forming regions and a number of cold dark clouds, including TMC-1, L134N, and B335. They used the 12 m NRAO telescope, whose half-pwer beamwidth (HPBW) is about 70" at 93 GHz (about three times bigger than the beam of the Haystack antenna at the same frequency) and the filter banks with 100 kHz resolution (10 times lower than in our survey).

The main conclusion of these works is that N_2H^+ is a selective tracer of extended and quiescent gas. In fact, it is not present in hot and shocked gas (see also Bachiller 1996), it does not show evidence of line wings indicating outflow motions (in contrast to spectra of HCO⁺), and its fractional abundance tends to decrease going from cold to warm regions. More recently, Turner (1995) deduced that N_2H^+ can only be formed in well-shielded regions, where photoprocesses are unimportant, suggesting that this molecular ion is a very good tracer of dense gas, similar to NH₃. This statement has been confirmed by Hirahara et al. (1995), who mapped N_2H^+ in TMC-1 and found a good correlation with NH₃ distribution in the same core and an anticorrelation with carbon chain molecules.

2.2. C₃H₂

The first detection of cyclopropenylidene (C_3H_2) is due to Thaddeus, Guélin, & Linke (1981). However, only four years later this detection was identified and observed toward many directions in the Galaxy (Matthews & Irvine 1985; Thaddeus, Vrtilek, & Gottlieb 1985; Vrtilek, Gottlieb, & Thaddeus 1987). Bell et al. (1988) used the 12 m NRAO telescope to survey C_3H_2 and C_3HD in cold interstellar clouds. The NRAO, FCRAO, and Haystack antennas were used by Madden et al. (1989) in their survey of galactic sources. Higher spatial and spectral resolution observations of several transitions of C_3H_2 were performed by Cox, Walmsley, & Güsten (1989), who observed about 30 dark cloud sources (most of them in the Taurus molecular complex) using the 100 m Effelsberg and the 30 m IRAM antennas. They found that, unlike N_2H^+ , the cyclopropenylidene abundance is correlated with that of cyanopolyynes, suggesting that these two species undergo the same kind of chemistry. Nine of the 30 sources of Cox et al. (1989) are in our sample, and we will compare them with our results in § 5.4.2.

2.3. CCS

The CCS radical was also first detected in space (Kaifu et al. 1987) and then identified in the laboratory (Saito et al. 1987). Suzuki et al. (1992, hereafter SYO) performed a survey of CCS in a sample of 49 dark cloud cores using the 45 m Nobeyama radio telescope. Ten of these cores are also in our sample. The spatial resolution of the SYO observations is comparable to the HPBW of the 37 m Haystack antenna at 45 GHz, but their spectral resolution is worse than in our observations by a factor of about 4. The conclusion of SYO was that CCS is more abundant in starless cores, where "early time" chemistry may apply, whereas NH_3 tends to be more abundant in star-forming regions. This point was also stressed by Hirahara et al. (1992), who showed an anticorrelation between CCS and NH_3 across

the TMC-1 core. We will further discuss this point in § 5.4.3.

Very high spectral resolution observations of CCS observations have been recently carried out at NASA's DSN 70 m Goldstone telescope by Velusamy, Kuiper, & Langer (1995) toward B335, by Kuiper, Langer, & Belusamy (1996) toward L1498, and by Wolkowitch et al. (1997) to determine physical conditions in L1498 and the TMC-1D cores.

3. OBSERVATIONS

Observations of C_3H_2 at 85338.905 MHz and N_2H^+ at 93173.777 MHz were made in 1994 January–February and 1995 January–March; those of CCS at 45379.033 MHz were made 1994 July. The frequency used for N_2H^+ is that derived by Caselli, Myers, & Thaddeus (1995). For N_2H^+ and C_3H_2 , we observed left and right circular polarization simultaneously with frequency switching using half the correlator for each polarization. Using a bandwidth of 17.8 MHz, we had a frequency resolution of 10.5 kHz, which provided a velocity resolution of 0.037 km s⁻¹ for C_3H_2 and 0.034 km s⁻¹ for N_2H^+ . For CCS, we used a single receiver and a bandwidth of 5.9 MHz, providing a velocity resolution of 0.012 km s⁻¹. All N_2H^+ and C_3H_2 spectra were Gaussian-smoothed to a resolution of 0.034 km s⁻¹ and then resampled to provide 1000 points with resolution

TABLE 1 Positions Observed

			-		
Source	Right Ascension (1950)	Declination (1950)	$V_{\rm LSR}$ (km s ⁻¹)	Infrared Association	Reference
Per 4	03 26 12.2	31 17 13	7.5	Y	1
Per 5	03 26 45.5	31 28 48	8.1	Ŷ	1
Per 6	03 27 10.3	30 12 34	5.8	Ŷ	1
Per 7	03 29 39.5	30 49 50	6.7	Ŷ	1
Per 9	03 30 10.4	31 10 14	6.9	Ŷ	1
B5	03 44 28.7	32 43 30	10	Ŷ	2
B5:N	03 44 28.7	32 44 30	10	Ŷ	2
B5:S	03 44 33.4	32 42 30	10	Ŷ	2
L1389	04 00 38.0	56 47 59	-4.7	Ŷ	3
L1489	04 01 45.0	26 11 33	7	Ŷ	2
L1498	04 07 50.0	25 02 13	7.7	Ν	2
L1495	04 11 02.7	28 01 58	6.8	Y	2
L1400G	04 21 12.1	54 12 20	3.4	Ν	2
B217	04 24 42.5	26 11 13	7	Y	2
L1524	04 26 26.0	24 29 26	6.5	Ŷ	2
L1400K	04 26 51.0	54 45 27	3	N	2
TMC-2A	04 28 54.0	24 26 27	6	Y	2
TMC-2	04 29 43.0	24 18 54	6	Ν	2
L1536	04 30 26.0	22 36 10	5.5	Y	2
L1534	04 36 31.2	25 35 56	6	Y	2
L1527	04 36 49.3	25 57 16	6	Y	2
TMC-1(NH ₃)	04 38 19.0	25 42 30	5	Ν	2
TMC-1C2	04 38 25.5	25 56 00	5	Ν	2
TMC-1C	04 38 34.5	25 55 00	5	Y	2
TMC-1(CS)	04 38 38.9	25 35 00	5.6	Ν	4
L1517B	04 52 07.2	30 33 18	5.5	Ν	2
L1512	05 00 54.4	32 39 00	7	Ν	2
L1544	05 01 14.0	25 07 00	7	Ν	2
L1582A	05 29 11.9	12 28 20	10	Y	2
B35A	05 41 45.3	09 07 40	11.7	Y	2
L134A	15 50 58.1	$-04\ 26\ 36$	2.5	Ν	2
L183(1)	15 51 30.0	$-02\ 42\ 51$	2.5	Ν	5
L183(2)	15 51 32.4	-02 40 37	2.5	Ν	5
L183	15 51 35.7	-02 40 54	2.5	Ν	2
L1681B	16 24 33.8	-24 36 47	3.5	Ν	2
L1696A	16 25 30.0	$-24\ 12\ 32$	3	Ν	2
L43E1	16 31 42.1	-15 40 50	0	Y	2
L43E	16 31 46.3	-15 40 50	0	Y	2

Infrared Association	Reference
Y	2
Y	2
Y	2
Y	2
Ν	2
Ν	2
Y	3

TABLE 1—Continued

Source	(1950)	(1950)	$(\mathrm{km} \mathrm{s}^{-1})$	Association	Reference
	16 44 22.3	-09 30 02	3	Y	2
	16 44 33.7	-13 54 03	4	Y	2
L234A	16 45 21.0	-10 46 33	3	Y	2
L234E	16 45 22.6	-105143	3	Y	2
	16 47 21.0	-18 01 00	6	Ν	2
368	17 19 36.0	-23 47 13	3.5	Ν	2
.483	18 14 50.5	-04 40 49	5.4	Y	3
3133	19 03 25.3	-065720	12.3	Ν	2
	19 24 26.4	23 52 37	10	Y	2
3335	19 34 33.3	07 27 00	8	Y	2
3335(IR)	19 34 35.3	07 27 34	8	Y	6, 7
L1152(IR)	20 35 19.4	67 42 31	2.5	Y	6
	20 35 24.0	67 43 53	2.5	Y	2
L1155C	20 43 00.0	67 41 47	2.5	Ν	2
L1082C	20 50 19.5	60 07 40	-2.5	Ν	2
L1082A	20 52 20.7	60 03 14	-2.5	Y	2
L1228D	20 58 11.0	77 24 00	-7.5	Y	3
L1228D(IR)	20 58 14.5	77 24 05	-8	Y	6
	20 59 46.3	68 01 04	3	Y	2
	21 00 44.4	78 11 00	-7.5	Y	2
L1172A	21 01 45.0	67 42 13	2.8	Y	2
L1172A(IR)	21 01 44.2	67 42 23	2.7	Y	6
3361	21 10 35.0	47 12 01	2.4	Y	2
L1031B	21 45 32	47 18 13	4	Y	2
L1031C	21 44 35.6	47 04 20	4.7	Y	2
	22 26 37.1	68 46 52	-4.3	Y	3
L1251A(NH ₃)	22 29 34.1	74 58 51	-4	Y	2
L1251A(IR)	22 29 03.3	74 58 51	-4	Y	6
L1251A2	22 30 04.8	74 57 51	-4	Y	2
L1251C	22 34 37.5	75 02 32	-5	Y	3
L1251E	22 38 10.8	74 55 50	-4	Y	3
L1262A	23 23 32.2	74 01 45	4	Y	2
L1262A(IR)	23 23 48.7	74 01 08	3.9	Y	6

Note.—Units of right ascension are hours, minutes, and seconds, and units of declination are degrees, arcminutes, and arcseconds. (NH_3) or (CS) after a core name implies a peak position of NH_3 or CS, respectively, which is different from the position with the core name given in BM. Other position offsets are designated with a numeral after the name.

REFERENCES.—(1) Ladd et al. 1994; (2) BM; (3) Benson, unpublished data; (4) Hirahara et al. 1992; (5) Ungerechts, Walmsley, & Winnewisser 1980; (6) *IRAS* Point Source Catalog 1988; (7) This observed position is not the correct *IRAS* position for which the declination is $7^{\circ}27'24''$.

of 0.034 km s⁻¹. Main-beam efficiencies were $\sim 20\%$ at 85 and 93 GHz and 45% at the frequency of the CCS line. Sources whose observations are reported here were previously observed in lines of NH₃ by BM and Ladd, Myers, & Goodman (1994).

The source list given in Table 1 was mostly derived from the NH_3 observations given by BM. The position used is the peak of the NH_3 map and not necessarily the position of an embedded infrared source. For a few sources, we have also observed at the position of the embedded source. Those positions are labeled with an "(IR)" in Table 1. A few other sources were taken from the literature and unpublished observations. The reference for each position and for the NH_3 observations is given in the table.

4. RESULTS

The results of the observations are given in Tables 2, 3, and 4. Table 2 presents the values for the hyperfine fits of the N_2H^+ spectra and derived column density. Objects marked with an asterisk in Table 2 have not been included in our study of chemical and physical properties described in § 5. Tables 3 and 4 give the results of Gaussian fits to the single features of C_3H_2 and CCS. We detected N_2H^+ in 60 of the 64 positions observed (94%) and C_3H_2 in 59 of the 70 positions observed (84%). CCS was detected in 15 of the 20 observed positions (75%). Thus, these molecules are readily observed in places where the NH_3 emission is strong. Welldefined $N_2H^+(1-0)$ spectra toward a quiescent starless core, L1512, and a core with a young embedded star, L483, are shown in Figure 1, where the seven hyperfine components are clearly resolved.

Several of the spectra show asymmetric line shapes such as those predicted for infalling material. These line shapes have been noted previously by Zhou et al. (1993), Myers et al. (1995), Wang et al. (1995), Mardones et al. (1997), and Gregersen et al. (1997) for 3 mm lines. Figure 2 shows several interesting spectra with unusual line shapes in order of "decreasing evidence" of infall asymmetry. We find strong correlation (correlation coefficient ≥ 0.999) between the velocities of N₂H⁺, C₃H₂, CCS, and NH₃. This implies that the motions of the ion N_2H^+ are very similar to those of the neutral species. The velocities for NH_3 and N_2H^+ are from the multicomponent fits, and those for C₃H₂ and CCS are from a single Gaussian fit. In sources where the velocity differs, it is usually because of asymmetric line shapes preventing accurate Gaussian fits. The histogram of the velocity difference $V_{LSR}(N_2H^+) - V_{LSR}(C_3H_2)$ shown in Figure 3 illustrates this point, which will be further discussed in § 5.1.

Figure 4 shows the strong correlation of the line widths with those of NH_3 . From linear least-square fits, we obtain

the following:

$$\Delta v(C_3H_2) = (0.11 \pm 0.03) + (0.93 \pm 0.06)\Delta v(N_2H^+), \quad (1)$$

$$\Delta v(\mathrm{NH}_3) = (0.05 \pm 0.02) + (0.87 \pm 0.05) \Delta v(\mathrm{N}_2\mathrm{H}^+) , \quad (2)$$

$$\Delta v(\text{CCS}) = (0.04 \pm 0.06) + (1.1 \pm 0.2)\Delta v(\text{N}_2\text{H}^+), \quad (3)$$

with linear correlation coefficients R = 0.93, 0.94, and 0.91, respectively. In the Δv (CCS) versus Δv (N₂H⁺) plot, we included CCS data from SYO, as explained in § 5.4.3. The widths for C₃H₂ and CCS were found by fitting a single Gaussian, whereas those for NH₃ and N₂H⁺ were obtained from multicomponent fits utilizing all the features and accounting for saturation broadening. There is no significant difference between the fits for cores with stars and starless cores apart from the absence of starless cores with observed line widths greater than 0.5 km s⁻¹ (the only exception being the CCS line width toward TMC-1, as measured by SYO). Also, most of the cores are primarily thermally supported; in particular, $\Delta v_{NT} > \Delta v_T$ in 11%, 18%, 30%, and 37% of the cores (reported in Fig. 4) observed in NH₃, N₂H⁺, CCS, and C₃H₂, respectively.

The correlations between the antenna temperatures, excitation temperatures, optical depths, and column densities (see § 5) are not as strong as the correlations among velocity and among line width. This result is plausible, since the line velocities and widths are not sensitive to variations in abundance, optical depth, and excitation temperature from molecule to molecule and from line to line. Also, it must be remembered that we have observed only a single position in this survey. The position of peak NH₃, which determined the source list was based on maps made at Haystack Observatory with 1' spacing and 1'.4 FWHM. The spatial resolution of the other molecules is from 2 to 3.5 times finer. Mapping has shown that for several sources the peak of the N_2H^+ map is one or more beams away from the nominal NH₃ peak (Caselli et al. 1998a). Kuiper et al. (1996) show an offset of the peak of the 22 GHz CCS emission from the NH₃ peak by over 1' and VLA observations of the 22 GHz CCS emission from B335 (Velusamy et al. 1995) show an absence of CCS emission from the central 10" of the core. The fact that we have not observed at the peak of the molecules observed with higher spatial resolution can affect the correlations of temperatures and optical depths.

5. DISCUSSION

5.1. Kinematic Similarity of N_2H^+ , NH_3 , and C_3H_2 Lines

The narrow widths of the lines reported in this paper and of the lines of NH_3 reported in BM afford a good opportunity to compare with high precision the velocities and line widths in a large sample of low-mass molecular cloud cores. Velocities and widths are reported here for 60 cores in N_2H^+ , 59 in C_3H_2 , and 15 in CCS, all with typical precision 0.01–0.03 km s⁻¹, according to single- or multiple-Gaussian fitting programs.

TABLE 2 Observations of N_2H^+

				- 2			
Source (1)	T _{ex} (K) (2)	$(\mathrm{km \ s}^{-1})$ (3)	$\begin{array}{c} \Delta V \\ (\mathrm{km} \ \mathrm{s}^{-1}) \\ (\mathrm{4}) \end{array}$	τ (5)	Area (K* km s ⁻¹) (6)	$\begin{array}{c}\Delta T^*_{\mathrm{A,rms}}\\(\mathrm{K})\\(7)\end{array}$	$N \times 10^{-12} \\ (cm^{-2}) \\ (8)$
Per 4	7.3 (1.3)	7.55	0.35	3 (1)	0.79 (0.02)	0.035	5 (1)
Per 5	6.5 (0.9)	8.20	0.37	3 (1)	0.76 (0.01)	0.029	5 (1)
Per 6	5.7 (1.4)	5.83	0.30	3 (1)	0.41 (0.01)	0.029	3 (1)
Per 7	4.2 (0.2)	6.84	0.40	7 (1)	0.63 (0.01)	0.025	6 (1)
Per 9 ^a	3.2 (0.5)	6.77	0.42	6 (6)	0.18 (0.02)	0.045	4 (4)
B 5 ^a	5.8 (5.0)	10.26	0.43	2(3)	0.38 (0.03)	0.068	2 (4)
B5:N	5.8 (1.1)	10.12	0.31	2 (1)	0.44 (0.01)	0.026	3 (1)
B5:S	5.5 (0.4)	10.25	0.44	5 (1)	0.92 (0.01)	0.023	7 (1)
L1389	4.2 (0.6)	-4.59	0.30	5 (2)	0.38 (0.02)	0.038	3 (1)
L1489	4.5 (0.5)	6.76	0.19	15 (4)	0.58 (0.02)	0.058	7 (2)
L1498	4.2 (0.4)	7.82	0.25	9 (2)	0.42 (0.02)	0.047	5 (1)
L1495	5.8 (1.1)	6.83	0.25	4 (1)	0.60 (0.02)	0.045	4 (1)
L1400G				•••	•••	0.023	•••
B217	5.2 (0.8)	7.01	0.35	4 (1)	0.62 (0.02)	0.045	5 (2)
L1524					•••	0.047	
L1400K ^a	3.4 (0.2)	3.25	0.21	13 (4)	0.22 (0.01)	0.029	4 (1)
TMC-2A	4.9 (0.4)	5.94	0.21	13 (2)	0.73 (0.02)	0.052	8 (1)
TMC-2	5.3 (0.9)	6.21	0.32	4 (1)	0.60 (0.02)	0.046	4 (1)
L1536	5.6 (0.4)	5.56	0.22	6 (1)	0.59 (0.01)	0.028	4 (1)
L1534	4.9 (0.7)	6.32	0.42	4 (1)	0.65 (0.02)	0.040	5 (2)
L1527	4.3 (0.3)	5.93	0.31	11 (2)	0.68 (0.02)	0.045	8 (1)
$TMC - 1(NH_3)$	5.6 (0.4)	5.89	0.39	6 (1)	0.95 (0.01)	0.028	7 (1)
TMC-1C2	3.6 (0.2)	5.16	0.21	14 (3)	0.30 (0.01)	0.033	5 (1)
TMC-1C	3.3 (0.1)	5.24	0.22	20 (3)	0.26 (0.01)	0.020	6 (1)
TMC-1(CS)	3.8 (0.3)	5.70	0.43	7 (2)	0.50 (0.02)	0.038	6 (1)
L1517B	4.7 (0.9)	5.82	0.23	4 (2)	0.32 (0.02)	0.040	3 (1)
L1512	5.0 (0.1)	7.11	0.19	8 (1)	0.47 (0.01)	0.010	4 (1)
L1544	4.3 (0.4)	7.12	0.22	12 (2)	0.48 (0.02)	0.045	6 (1)
L1582A	4.0 (0.7)	10.19	0.37	4 (2)	0.29 (0.01)	0.031	3 (1)
B35A	4.1 (0.4)	11.58	0.71	6 (1)	0.88 (0.02)	0.041	9 (2)
L134A	4.9 (1.9)	2.72	0.22	3 (2)	0.24 (0.02)	0.039	2 (1)
L183(1)	5.3 (0.4)	2.49	0.25	9 (1)	0.78 (0.02)	0.044	7 (1)
L183	5.3 (0.6)	2.43	0.24	6 (1)	0.65 (0.02)	0.043	5 (1)
L1681B						0.060	
L1696A	12.0 (7.5)	3.42	0.26	1 (1)	0.55 (0.01)	0.035	4 (3)

Source (1) L43E L260 L234A L234A	T_{ex} (K) (2) 5.5 (0.3)	$(\mathrm{km}\ \mathrm{s}^{-1})$ (3)	$(\mathrm{km \ s^{-1}})$ (4)	τ (5)	Area (K* km s ⁻¹)	$\Delta T^*_{A, rms}$	$N \times 10^{-12}$
L43E L260 L158 L234A	5.5 (0.3)			(3)	(6)	(K) (7)	(cm ²) (8)
L260 L158 L234A		0.76	0.27	10 (1)	1.05 (0.02)	0.039	9 (1)
L158 L234A	3.6 (0.2)	3.47	0.22	14 (3)	0.34 (0.01)	0.030	5 (1)
L234A	3.9 (0.5)	3.92	0.25	5 (2)	0.24 (0.01)	0.028	2 (1)
I 224E8	4.6 (0.5)	2.92	0.23	5 (1)	0.38 (0.01)	0.026	3 (1)
L234E	3.5 (0.5)	3.16	0.23	6 (3)	0.17 (0.01)	0.029	2 (1)
L63	4.1 (0.5)	5.80	0.24	7 (3)	0.37 (0.02)	0.042	3 (1)
B68 ^a	3.7 (0.4)	3.34	0.20	19 (5)	0.35 (0.02)	0.049	6 (2)
L483	6.4 (0.1)	5.37	0.35	16 (1)	2.24 (0.01)	0.017	24 (1)
B133 ^a	5.0 (0.0)	12.11	0.62	1 (1)	0.14 (0.02)	0.037	1 (1)
L778	4.9 (0.5)	9.90	0.47	6 (1)	0.93 (0.02)	0.051	8 (2)
B335 ^a	3.3 (0.3)	8.34	0.32	5 (2)	0.16 (0.01)	0.018	2 (1)
B335(IR)	5.2 (0.3)	8.35	0.38	9 (1)	1.10 (0.02)	0.036	10 (1)
L1152	5.0 (0.0)	2.46	0.37	1 (1)	0.20 (0.01)	0.023	1 (0.1)
L1155C	4.3 (1.1)	2.68	0.36	3 (2)	0.31 (0.01)	0.033	2 (2)
L1082C ^a	3.6 (0.5)	-2.52	0.38	5 (2)	0.26 (0.01)	0.028	3 (2)
L1082A	3.6 (0.2)	-2.22	0.37	12 (3)	0.44 (0.01)	0.031	8 (2)
L1228D	5.7 (0.1)	-8.04	0.61	7 (1)	1.65 (0.01)	0.018	14 (1)
L1174	4.9 (0.7)	2.31	0.59	4 (1)	0.90 (0.02)	0.047	7 (2)
L1228 ^a	3.2 (0.2)	-7.47	0.34	15 (5)	0.29 (0.01)	0.025	8 (2)
L1172A ^a	4.2 (0.5)	2.83	0.60	5 (2)	0.73 (0.02)	0.047	7 (2)
B361 ^a	3.0 (0.2)	2.79	0.47	12 (5)	0.17 (0.01)	0.024	7 (3)
L1031B	7.0 (3.1)	4.11	1.10	1 (1)	1.09 (0.02)	0.048	7 (5)
L1031C	•••			•••	•••	0.048	
L1221 ^a	3.0 (0.2)	-4.63	0.65	6 (4)	0.16 (0.01)	0.023	5 (3)
L1251A	4.9 (0.5)	-3.90	0.44	5 (1)	0.71 (0.02)	0.033	5 (1)
L1251A2	5.0 (0.0)	-4.17	0.35	1 (4)	0.31 (0.02)	0.038	2 (1)
L1251C ^a	3.1 (0.4)	-4.71	0.62	6 (5)	0.18 (0.01)	0.030	5 (4)
L1251E	5.0 (0.0)	-3.62	0.93	1 (1)	0.82 (0.02)	0.032	4 (1)
L1262A	4.7 (0.4)	3.91	0.45	7 (1)	0.92 (0.02)	0.047	8 (2)

TABLE 2-Continued

NOTE.—Cols. (2)–(5) give the results of the seven-component fit to the spectra using the hyperfine structure (hereafter hfs) fitting in CLASS (GAG) with the line frequencies determined by Caselli et al. (1995). The excitation temperature T_{ex} (col. [2]) has been derived from the hfs fit, assuming a unity-filling factor and a main-beam efficiency of 0.2. The uncertainty in the velocity fits in col. (3) are typically less than 0.01 km s⁻¹. The uncertainty is between 0.02 and 0.0.06 km s⁻¹ for B5, Per 9, B133, B361, L1221, and L1251C. The same sources also have larger than the typical uncertainty of ≤ 0.03 km s⁻¹ in the line width. In col. (5), τ is the total optical depth (the sum of the peak optical depths of the seven hyperfine components). Col. (6) lists the integrated intensity in units of antenna temperature times velocity. The uncertainty in the area is given by $\sigma_{Area} = \Delta T^*_{A,rms} \Delta v_{res}(N_{ch})^{1/2}$, where $\Delta T^*_{A,rms}$ is the 1 σ level of the noise in the off-line channels (see col. [7]), $\Delta v_{res} = 0.034$ km s⁻¹ is the velocity width of a spectral channel, and N_{ch} is the number of channels in the integrated intensity. For calculation of the N₂H⁺

column density in col. (8), see the Appendix. ^a These objects show a faint N_2H^+ emission with $T_A^*/\Delta T_{A,rms}^* < 5$.

The line velocities are highly correlated from one line to the next, as shown in Figure 3. They are best compared between N_2H^+ and C_3H_2 , since the N_2H^+ line frequency has been determined to a high degree of precision, $\sim 1 \text{ kHz}$ or 0.003 km s⁻¹, with respect to the C_3H_2 line frequency (Caselli et al. 1995). For these two lines, the velocity difference $\Delta V = V_{LSR}(N_2H^+) - V_{LSR}(C_3H_2)$ has a mean and standard error of the mean -0.024 ± 0.010 km s⁻¹ for 41 cores with observations in both lines and, excluding higher noise measurements, with $\sigma_{\Delta V} > 0.025$ km s⁻¹. This mean velocity difference is marginally statistically significant, smaller than the velocity resolution, and comparable to the typical uncertainty of a measurement of velocity difference in an individual core. The velocity difference is also comparable to the uncertainty associated with the rest frequency of the C_3H_2 line (Vrtilek et al. 1987). Thus it is not clear whether the mean velocity difference represents a statistically significant effect and, if so, whether this has a physical or observational basis. However, we can say with confidence that the absolute velocity difference between the two lines is generally smaller than 0.03 km s^{-1} .

The observed line widths have mean and standard error of the mean 0.37 \pm 0.02 km s⁻¹ for N₂H⁺, 0.46 \pm 0.02 km s⁻¹ for C₃H₂, and 0.38 \pm 0.06 km s⁻¹ for CCS. These

numbers are similar to each other and to the corresponding 0.36 ± 0.03 km s⁻¹ for the NH₃ sample of BM. These widths are also correlated from core to core, as is illustrated in Figure 4. After removal of the thermal contribution of the observed tracer from each of these typical widths, the resulting nonthermal line width $\Delta v_{\rm NT}$ is, respectively, 0.35, 0.46, and 0.36 km s⁻¹.

These nonthermal widths are each comparable to or less than the corresponding width 0.45 km s⁻¹ of the velocity distribution of the molecule of mean mass at temperature 10 K. Consequently, the typical core in our sample has non-thermal motions that are comparable to or less than its thermal motions.

It is sometimes suggested that the line widths of NH_3 in low-mass cores are anomalously low because NH_3 is easily destroyed on the inside and outside of cores, leaving only the quiescent gas available for the NH_3 lines to trace. The present results suggest that the kinematic properties of NH_3 are not peculiar to NH_3 but instead are seen in several other molecular tracers as well.

5.2. Ion-neutral Drift

The small difference between N_2H^+ and C_3H_2 velocities is noteworthy because it is also an ion-neutral velocity dif-

TABLE 3 Observations of C_3H_2

Source	T* (K)	V_{LSR} (km s ⁻¹)	Δv (km s ⁻¹)	Area (K* km s ⁻¹)	$\Delta T^*_{\mathrm{A,rms}}$ (K)	$N imes 10^{-12}$ (cm ⁻²)	τ
Per 4					0.093		
Per 5	0.33	8.20 (0.01)	0.43 (0.03)	0.15 (0.01)	0.052	5 (1)	0.5 (0.1)
Per 6	0.26	5.85 (0.01)	0.28 (0.02)	0.08(0.01)	0.040	2.4 (0.6)	0.37(0.08)
Per 9	0.27	6.90 (0.02)	0.41 (0.05)	0.12 (0.01)	0.054	4 (1)	0.4 (0.1)
B5	0.29	10.27 (0.02)	0.48 (0.04)	0.15 (0.01)	0.056	5 (1)	0.4 (0.1)
B5:N	0.44	10.14 (0.01)	0.45 (0.03)	0.21 (0.01)	0.070	8 (2)	0.7 (0.2)
B5:S		•••	•••		0.067	•••	••••
L1389					0.066		
L1489	0.50	6.77(0.01)	0.37(0.01)	0.20(0.01)	0.034	7.6 (0.9) 5.3 (1.0)	0.9(0.1)
L1498	0.45	6 85 (0.01)	0.30(0.02) 0.32(0.02)	0.14(0.01) 0.16(0.01)	0.048	5.5 (1.0) 6 (1)	0.8(0.1) 0.8(0.1)
L1400G					0.065	• (1)	
B217	0.44	7.00 (0.01)	0.40 (0.02)	0.19 (0.01)	0.049	7 (1)	0.7 (0.1)
L1524	0.31	6.41 (0.01)	0.43 (0.03)	0.14 (0.01)	0.046	5 (1)	0.4 (0.1)
L1400K	0.44	3.32 (0.01)	0.24 (0.02)	0.11(0.01)	0.065	4 (1) 5 (1)	0.7 (0.2)
$TMC = 2A \dots TMC = 2$	0.44	5.90(0.01) 6.23(0.01)	0.30(0.02) 0.43(0.02)	0.14(0.01) 0.23(0.01)	0.052	9(2)	0.7(0.1) 0.9(0.2)
L1536	0.50	5.61 (0.01)	0.32 (0.02)	0.18 (0.01)	0.065	7 (2)	1.0 (0.2)
L1534	0.49	6.42 (0.01)	0.44 (0.03)	0.23 (0.01)	0.071	9 (2)	0.8 (0.2)
L1527	0.77	5.84 (0.01)	0.57 (0.02)	0.46 (0.02)	0.086	30 (13)	2.2 (0.9)
$TMC - 1(NH_3)$	0.76	5.81 (0.01)	0.51 (0.02)	0.41 (0.01)	0.064	26 (8)	2.1 (0.6)
$TMC - 1C2 \dots TMC - 1C$	0.32	5.28 (0.02)	0.41 (0.03) 0.39 (0.03)	0.14(0.01) 0.16(0.01)	0.058	4 (1) 6 (1)	0.5(0.1)
TMC = 1(CS)	0.82	5.83 (0.01)	0.49 (0.01)	0.43(0.01)	0.062	37 (20)	3 (2)
L1517B	0.36	5.83 (0.01)	0.32 (0.03)	0.12 (0.01)	0.064	4 (1)	0.5 (0.1)
L1512	0.44	7.16 (0.01)	0.26 (0.02)	0.12 (0.01)	0.057	4 (1)	0.7 (0.2)
L1544 ^a	0.39	7.17 (0.02)	0.42 (0.03)	0.17 (0.01)	0.080	6 (2)	0.6 (0.2)
L1582A					0.073		
L134A	0.27	2.74 (0.01)	0.27(0.03)	0.31(0.02) 0.06(0.01)	0.084	10(3) 1.8(0.5)	0.4(0.1) 0.28(0.07)
L183(1)	0.44	2.43 (0.01)	0.32 (0.03)	0.15 (0.01)	0.063	6 (1)	0.7 (0.2)
L183	0.40	2.48 (0.01)	0.25 (0.01)	0.11 (0.01)	0.027	3.7 (0.4)	0.63 (0.06)
L1681B					0.073		
L1696A	0.54	3.42 (0.01)	0.29 (0.03)	0.17(0.01)	0.049	7 (1)	1.0 (0.2)
L43E1	0.33	0.39(0.01) 0.84(0.01)	0.32(0.02) 0.45(0.03)	0.19(0.01) 0.23(0.01)	0.039	8 (2) 9 (2)	1.0(0.2) 0.8(0.2)
L260	0.34	3.60 (0.01)	0.20 (0.03)	0.07 (0.01)	0.059	2.4 (0.7)	0.5(0.2)
L158 ^a	0.17	3.88 (0.01)	0.21 (0.03)	0.04 (0.01)	0.042	1.1 (0.4)	0.22 (0.07)
L234A	0.53	2.93 (0.01)	0.27 (0.02)	0.15 (0.01)	0.069	6 (2)	1.0 (0.2)
L234E	0.39	3.21 (0.01)	0.34 (0.02)	0.14(0.01)	0.052	5(1)	0.6(0.1)
B68	0.45	3.80(0.01) 3.31(0.01)	0.27(0.02) 0.28(0.02)	0.12(0.01) 0.13(0.01)	0.049	4.4 (0.9) 5 (1)	0.7(0.1) 0.8(0.2)
L483	0.57	5.38 (0.02)	0.44 (0.02)	0.26 (0.01)	0.050	11(2)	1.1 (0.2)
B133	0.39	12.13 (0.01)	0.39 (0.02)	0.16 (0.01)	0.040	6 (1)	0.6 (0.1)
L778	0.21	9.98 (0.02)	0.71 (0.04)	0.16 (0.01)	0.038	5 (1)	0.29 (0.07)
B335	0.37	8.36 (0.01)	0.45 (0.02)	0.18(0.01)	0.049	6(1)	0.6(0.1)
L1152(IR)	0.38	2 70 (0.01)	0.50(0.02) 0.54(0.01)	0.20(0.01) 0.28(0.01)	0.033	0.9 (0.9) 10 (1)	0.38(0.08) 0.82(0.08)
L1152 ^a	0.27	2.60 (0.03)	0.49 (0.06)	0.14 (0.025)	0.080	4 (2)	0.4 (0.2)
L1155C	•••		•••		0.057	•••	•••
L1082C ^a	0.27	-2.46(0.03)	0.45 (0.12)	0.13 (0.03)	0.082	4 (2)	0.4 (0.2)
L1082A ^a	0.30	-2.10(0.02)	0.27 (0.04)	0.08(0.01)	0.082	3(1)	0.4(0.2)
L1228D	0.35	= 7.99 (0.02) = 8.10 (0.01)	0.74(0.03) 0.78(0.01)	0.20(0.01) 0.31(0.01)	0.000	8 (2) 10 6 (0 8)	0.3(0.1) 0.57(0.04)
L1174	0.32	2.94 (0.02)	0.75 (0.04)	0.26 (0.01)	0.046	8 (2)	0.5 (0.1)
L1228 ^a	0.13	-7.38 (0.03)	0.53 (0.09)	0.07 (0.01)	0.042	2.0 (0.9)	0.16 (0.07)
L1172A	0.25	2.88 (0.02)	0.62 (0.05)	0.16 (0.01)	0.048	5 (1)	0.34 (0.09)
L1172A(IR)	0.20	2.83 (0.01)	0.74 (0.03)	0.16 (0.01)	0.020	4.6 (0.6)	0.27 (0.04)
B301	0.43	4 34 (0 02)		0.52 (0.02)	0.079	 18 (4)	0.7(0.2)
L1031C	0.29	4.78 (0.02)	0.51 (0.04)	0.16 (0.01)	0.052	5 (2)	0.4 (0.1)
L1221 ^a	0.18	-4.43 (0.03)	0.72 (0.06)	0.14 (0.01)	0.047	4 (1)	0.24 (0.08)
L1251A	0.31	-3.90 (0.01)	0.54 (0.03)	0.18 (0.01)	0.041	6 (1)	0.45 (0.08)
L1251A(IR)					0.048	5 (1)	
L1251A2	0.38	-4.17 (0.01)	0.38 (0.04)	0.15 (0.01)	0.063	5 (1)	0.0 (0.1)
L1251E	0.41	- 3.49 (0.02)	0.85 (0.03)	0.37 (0.01)	0.052	13 (3)	0.6 (0.1)
L1262A ^a	0.24	3.94 (0.02)	0.50 (0.05)	0.13 (0.01)	0.056	4 (1)	0.3 (0.1)
L1262A(IR)	0.23	4.09 (0.01)	0.62 (0.03)	0.15 (0.01)	0.033	4.5 (0.9)	0.31 (0.06)

Note.—The method of determining the column density and optical depth is given in the Appendix. ^a These objects have $T_A^*/\Delta T_{A,rms}^* < 5$.

T* (K)	V_{LSR} (km s ⁻¹)	Δv (km s ⁻¹)	Area (K* km s ⁻¹)	$\Delta T^*_{\mathrm{A,rms}}$ (K)	$N imes 10^{-12}$ (cm ⁻²)	τ
0.30	8.21 (0.02)	0.27 (0.05)	0.09 (0.01)	0.076	1.9 (0.7)	0.23 (0.07)
0.36	10.20 (0.02)	0.41 (0.04)	0.16 (0.01)	0.070	4 (1)	0.28 (0.07)
1.30	7.831 (0.003)	0.20 (0.01)	0.27 (0.01)	0.064	13 (2)	2.1 (0.3)
0.56	6.84 (0.01)	0.25 (0.02)	0.15 (0.01)	0.052	3.6 (0.7)	0.47 (0.08)
0.52	5.95 (0.01)	0.28 (0.02)	0.15 (0.01)	0.048	3.7 (0.5)	0.43 (0.05)
0.62	7.13 (0.01)	0.18 (0.02)	0.12 (0.01)	0.076	3.0 (0.7)	0.5 (0.1)
		•••	•••	0.042		·
				0.060		
0.55	2.46 (0.01)	0.25 (0.01)	0.14 (0.01)	0.045	3.6 (0.5)	0.46 (0.07)
0.22	0.75 (0.04)	0.69 (0.08)	0.16 (0.02)	0.074	3 (1)	0.16 (0.05)
0.33	3.47 (0.01)	0.21 (0.03)	0.07 (0.01)	0.059	1.6 (0.5)	0.25 (0.07)
		/		0.061		/
0.37	3.17 (0.01)	0.24 (0.02)	0.10 (0.01)	0.059	2.1 (0.6)	0.29 (0.07)
0.28	5.81 (0.02)	0.36 (0.04)	0.11 (0.01)	0.069	2.3 (0.6)	0.21 (0.05)
0.94	5.313 (0.005)	0.38 (0.01)	0.38 (0.01)	0.048	12 (2)	1.0 (0.1)
0.60	12.21 (0.01)	0.46 (0.02)	0.30 (0.01)	0.061	7 (2)	0.5 (0.1)
0.45	8.33 (0.01)	0.26 (0.01)	0.13 (0.01)	0.039	2.9 (0.2)	0.36 (0.03)
	,	/	,	0.075	,	/
				0.051		
0.25	-3.66 (0.04)	1.03 (0.09)	0.28 (0.02)	0.072	6 (2)	0.18 (0.08)
	T* (K) 0.30 0.36 1.30 0.56 0.52 0.62 0.55 0.22 0.33 0.37 0.28 0.94 0.60 0.45 0.25	$\begin{array}{c ccccccccccccccccccccccccccccccccccc$	$\begin{array}{c ccccccccccccccccccccccccccccccccccc$	$\begin{array}{c ccccccccccccccccccccccccccccccccccc$	$\begin{array}{c ccccccccccccccccccccccccccccccccccc$	$ \begin{array}{c ccccccccccccccccccccccccccccccccccc$

TABLE 4Observations of CCS

NOTE.—The method of determining the column density and optical depth is given in the Appendix.

^a These objects have $T_A^*/\Delta T_{A, \text{rms}}^* < 5$.



FIG. 1.—N₂H⁺(1–0) spectra toward the starless core L1512 in Taurus (*top*) and L483 (*bottom*), which is associated with an *IRAS* source. The hyperfine components of the L1512 spectrum have been labeled with the corresponding quantum numbers $F_1 F$. These spectra have been obtained at the 37 m Haystack antenna. The high spectral resolution ($\Delta v_{res} = 0.034$ km s⁻¹) allowed us to resolve the seven hyperfine components of the N₂H⁺(1–0) rotational transition.

ference. The ions feel magnetic forces directly, while the neutrals feel magnetic forces only indirectly through collisions with the ions. The high degree of consistency between ion and neutral velocities indicates that ion-neutral coupling is typically strong enough to prevent bulk motion between the center of mass of the ions and the center of mass of the neutrals at a level exceeding 0.03 km s^{-1} .

mass of the neutrals at a level exceeding 0.03 km s⁻¹. This upper limit $v_{D,\text{max}} \approx 0.03$ km s⁻¹ on the speed of ion-neutral drift in the core is, to our knowledge, the first reported observational constraint on the relative speed of ions and neutrals in star-forming dense cores. Its value is similar to the expected ion-neutral drift speed in cores due to ambipolar diffusion (e.g., Mestel & Spitzer 1956; Ciolek & Mouschovias 1995). The limit reported here is not a detection of ambipolar diffusion, but it indicates that ionneutral motions in dense cores do not significantly exceed those expected for ambipolar diffusion. Similarly, the drift time for ions and neutrals to move apart by a typical dense core radius, $r_{\rm core} \sim 0.05$ pc, must exceed $r_{\rm core}/v_{D,\rm max} = 2$ Myr. This drift time is greater by an order of magnitude than the dynamical time of a dense core, indicating that any ion neutral drift that occurs in cores can be considered a quasi-static process, as expected for ambipolar diffusion.

The relative abundance of ions and neutrals in low-mass cores has been measured experimentally to lie within a factor of a few of 10^{-7} , consistent with that expected from cosmic-ray ionization (Williams et al. 1998; Caselli et al. 1998b; McKee et al. 1993). The corresponding ion neutral coupling can be expressed as the ratio of core size to cutoff wavelength for MHD waves, W = 10. This level of coupling is strong enough to allow propagation of some MHD waves but weak enough to allow ambipolar diffusion with time scales of several Myr and drift speeds of order 0.01 km s⁻¹ in low-mass dense cores (Williams et al. 1998; Caselli et al. 1998b).

This upper limit $v_{D, \max} \approx 0.03$ km s⁻¹ on the speed of



FIG. 2.—Spectra of $C_3H_2(2_{1,2}-1_{0,1})$ (top) and the F_1 , $F = 0, 1 \rightarrow 1, 2$ component of the $N_2H^+(1-0)$ transition (bottom) are displayed for those cores showing asymmetric profiles. In these spectra we show only the feature of N_2H^+ at 93176.265 MHz, because it has no blending with nearby features and is generally optically thin. The vertical dotted line marks the V_{LSR} value deduced from N_2H^+ observations. Line shapes for L1544, B335(IR), B68, L1489, and L183(1) are consistent with models of cloud cores undergoing gravitational collapse. We found two new starless cores showing infall asymmetry: B68 and L183(1). In B133, the N_2H^+ line has been detected with low signal-to-noise and therefore has not been shown.

ion-neutral drift in the core also corresponds to a lower limit on the size scale of the magnetic field variation in the core. From the equation of motion for the ions (e.g., eqs. [47] and [55] in McKee et al. 1993), this minimum size scale $l_{B,\min}$ can be written

$$l_{B,\min} = \frac{B}{|\nabla \times B|_{\max}} = \frac{v_A^2}{v_{D,\max}v_{\min}},$$
 (4)

where $v_{\rm A}$ is the Alfvén speed in the core and $v_{\rm ni}$ is the ionneutral collision frequency. To evaluate this minimum size scale, we assume that the nonthermal line width arises from Alfvén waves whose kinetic energy is equal to the static field energy, so that $v_{\rm A} = [3/(8 \ln 2)]^{1/2} \Delta v_{\rm NT}$; that the rate coefficient for ion-neutral collisions is 2×10^{-9} cm³ s⁻¹ (Nakano 1984); and that the ionization is due to cosmic rays, so that $v_{\rm ni} = 2 \times 10^{-14} n^{1/2} s^{-1}$ for neutral gas density n and for standard values of the cosmic ray ionization rate (Elmegreen & Fiebig 1993). Then for $\Delta v_{\rm NT} = 0.35$ km s⁻¹, as for N₂H⁺ and for $n = (1-3) \times 10^4$ cm⁻³ indicated by NH₃ observations (BM), equation (4) gives $l_{B,\min} = 0.02-0.04$ pc.

This minimum size is comparable to the radii of dense core maps in the same tracers considered here (Caselli et al. 1998a), implying that the magnetic field in the typical core interior is relatively uniform—it does not have enough spatial variation to allow ion drift greater than ~ 0.03 km s⁻¹ with respect to the neutrals. Furthermore, the corresponding heating rate due to ion-neutral drift (see eq. [56] in McKee et al. 1993) is <1 × 10⁻²⁷ ergs cm⁻³ s⁻¹, less by an order of magnitude than the cosmic ray heating rate for the same density (Goldsmith & Langer 1978).

5.3. Unusual Line Profiles

In most cases the shapes of the observed lines are singlepeaked and symmetrical and are well fitted by Gaussian profiles, as expected for optically thin emission. However, in



FIG. 2.—Continued



FIG. 3.—Histogram of the velocity difference $V_{\text{LSR}}(N_2H^+)$ - $V_{\text{LSR}}(C_3H_2)$. The peak is approximately at zero (-0.024 \pm 0.010 km s⁻¹), which indicates a high degree of consistency between ion and neutral velocities.

a few cores the line profiles have either two peaks or asymmetrical shoulders, indicative of optically thick emission and systematic internal motions. This is evident in the C_3H_2 lines in B335 and L1544, already known to have self-



FIG. 4.—Comparison between (a) $\Delta v(C_3H_2)$, (b) $\Delta v(NH_3)$, and (c) $\Delta v(CCS)$ and $\Delta v(N_2H^+)$, where Δv is the observed line width. Cores with embedded stars are represented by filled dots, whereas empty circles are starless cores. The straight lines are the best fits to all the data in the figures (see text). The square box separates mostly thermal cores ($\Delta v_{\rm NT} < \Delta v_{\rm T}$, where $\Delta v_{\rm NT}$ and $\Delta v_{\rm T}$ are the nonthermal and thermal line widths of the molecule of mean mass) from those dominated by nonthermal motions ($\Delta v_{\rm NT} > \Delta v_{\rm T}$).

reversed profiles from earlier observations (e.g., Zhou et al. 1993; Tafalla et al. 1998). Figure 2 presents asymmetric spectra from several cores, including two starless cores not previously reported to have "infall asymmetry": B68 and L183(1). These are good candidates for follow-up spectroscopic and mapping observations.

5.4. Column Densities

5.4.1. N₂H⁺

Considering only those cores with $T_{\rm A}^*(N_2H^+)/\Delta T_{\rm A,rms}^* > 5$, from Table 2 we see that column density values range between 1×10^{12} cm⁻² (for L1152) and 24×10^{12} cm⁻² (L483). There is not a significant difference between cores with stars and starless cores, although cores associated with embedded objects have slightly higher N₂H⁺ column densities: $\langle N(N_2H^+) \rangle_{\rm star} = (6 \pm 4) \times 10^{12}$ cm⁻² and $\langle N(N_2H^+) \rangle_{\rm starless} = (4 \pm 2) \times 10^{12}$ cm⁻². The average column density in the entire sample is $\langle N(N_2H^+) \rangle =$ $(6 \pm 4) \times 10^{12}$ cm⁻². As pointed out at the end of § 4, the correlation between $N(N_2H^+)$ and $N(NH_3)$ is surprisingly very weak, given the similarity of the two molecules. This may be due to a different peak position of the N₂H⁺ emission with respect to the NH₃ maps, together with the higher spatial resolution of N₂H⁺ observations, which are more sensitive to the chosen coordinates.

5.4.2. C_3H_2

As in the case of N_2H^+ , no significant differences between cores with stars and starless cores are present. The average C_3H_2 column density in the whole sample is $\langle N(C_3H_2)\rangle =$ $(8 \pm 7) \times 10^{12}$ cm⁻². No correlations exist between $N(C_3H_2)$ and $N(N_2H^+)$.

5.4.3. CCS

Only three of the 20 sources observed in CCS (see Table 4) are in common with the SYO sample, so it is not possible to make detailed comparisons. In any case, we find a very good agreement for these three cores: $N(CCS)_{SYO}/N(CCS)_{this work} = 1.9, 1.3, and <1 for B5:N (B5)$ in SYO), L1498, and B335, respectively. Although the spectral resolution in our work is about seven times finer than that in the SYO survey, we have similar spatial resolution. Therefore, we decided to enlarge our CCS sample by including seven SYO cores that have been observed by us only in N_2H^+ and C_3H_2 [B5:N, TMC-2A, L1172A, L1031B, L1400K, TMC-1 (NH₃), and L1517B]. This inclusion allowed us to improve the statistical significance of correlations between column densities of CCS and the other two observed molecular species. No correlations are present between N(CCS) and $N(N_2H^+)$, but we found $N(C_3H_2) =$ $(3 \pm 3) + (0.8 \pm 0.3) N(CCS)$ with a linear correlation coefficient R = 0.52. This weak positive correlation was also noted by SYO and attributed to similarities in the chemical production of the two species.

There is a slight tendency for CCS to have higher column densities in starless cores, in agreement with SYO: $\langle N(\text{CCS}) \rangle_{\text{star}} = (6 \pm 4) \times 10^{12} \text{ cm}^{-2}, \langle N(\text{CCS}) \rangle_{\text{starless}} = (8 \pm 6) \times 10^{12} \text{ cm}^{-2}$, although this is not statistically significant. The highest CCS column density values $[N(\text{CCS}) > 10^{13} \text{ cm}^{-2}]$ are found in two starless cores (L1498 and TMC-1 [NH₃]) as well as in two cores associated with embedded stars (L483 and L1031B).

5.4.4. Abundance Variations

Column density ratios, which are independent of gas column density and can be regarded as abundance ratios, are needed to better underline possible chemical variations between the cores in our sample. The column density ratios $N(NH_3)/N(N_2H^+)$, $N(C_3H_2)/N(N_2H^+)$, $N(CCS)/N(N_2H^+)$, and $N(C_3H_2)/N(CCS)$ are listed in Table 5 for all cores with $T_A^*/\Delta T_{A,rms}^* > 5$. The sample has been separated into cores with stars and starless cores to look for chemical differences between the two classes of cores.

From the table it is clear that, on average, there are no significant variations between cores with stars and starless cores for the $N(NH_3)/N(N_2H^+)$ and $N(C_3H_2)/N(N_2H^+)$

abundance ratios. On the other hand, $N(CCS)/N(N_2H^+)$ is higher in starless cores by a factor of about 2, and $N(C_3H_2)/N(CCS)$ is higher in cores associated with stars by a similar factor, although the dispersion is larger. Considering the similarity between NH₃ and N₂H⁺, this result is in agreement with the finding of SYO, who explained this difference as due to an "evolutionary effect:" starless cores are younger than star-forming cores, and their chemical composition is characterized by higher abundances of "earlytime" molecules such as CCS and carbon-chain molecules. "Steady-state" species like NH₃ and N₂H⁺ have increased abundances with respect to CCS in cores associated with young stellar objects that may be in a more evolved evolu-

	ABU	NDANCE VARIATIONS		
Source	$N(NH_3)/N(N_2H^+) \times 10^{-2}$	$N(C_{3}H_{2})/N(N_{2}H^{+})$	$N(CCS)/N(N_2H^+)$	$N(C_3H_2)/N(CCS)$
		Cores with stars		
Per 5	0.21	1.0	•	
Per 6		1.0		
Per 7	0.21	0.58		
B5				1.3
B5:N		2.8	2.4	1.1
L1489	2.4	1.1		
L1495		1.5	0.9	1.7
B217	1.7	1.5		
TMC-2A	1.7	0.67	0.43	1.6
L1536	1.2	1.7		
L1534	2.0	1.8		
L1527	0.66	3.9	0.49	8.1
TMC-1C	2.5	0.86		
TMC-1C2	0.51	0.92		
L1582A	0.50			
B35A	0.4			
L260	3.0	0.45	0.30	1.5
L158	1.7			
L234A	1.7	2.0		
L234E				2.3
L483		0.48	0.50	0.96
L778	0.84	0.64		
B335				2.1
B335(IR)	0.82	0.72		
L1152	11.3			
L1082A	1.1		0.35	
L1228D		0.62	0.00	
L11220D	•••	12		•••
L1172A	•••	1.2		0.83
L1031B	0.59	27	22	12
L1251A	19	11	2.2	1.2
L1251A2	1.9	33		•••
L1251E	•••	36	•••	•••
L1262A	0.98	210		
Average	1.7 ± 2.2	1.5 ± 1.0	0.9 ± 0.8	2.1 + 2.0
		Starless cores	··· <u>-</u> ···	
T 1409	1.6	1 1	27	0.41
L1498	1.0	1.1	2.1	0.41
L1400K			•••	1.1
TMC-2	2.4	2.2	2	
$IMC - I(NH_3) \dots$	•••	3.6	2.6	1.4
1 MC-1(CS)		6.4		
L151/B	2.3	1.5	3.2	0.48
L1512	2.0	1.1	0.77	1.5
L1544	1.8		•••	•••
L134A	2.4	1.1	•••	•••
L183(1)		0.81		•••
L183	1.0	0.76	•••	•••
L1696A	1.4	1.9		
L63	2.9	1.3	0.68	1.9
B133		•••	•••	0.77
L1155C	2.1			
Average	2.0 ± 0.5	2.0 ± 1.6	2.0 ± 1.1	1.1 ± 0.5

TABLE 5

tionary phase compared with starless cores (see also Bergin & Langer 1997).

An interesting anticorrelation has been found between $N(C_3H_2)/N(CCS)$ and $N(CCS)/N(N_2H^+)$ (see Fig. 5): $N(C_3H_2)/N(CCS) = (1.7 \pm 0.2)-(0.3 \pm 0.1)N(CCS)/$ $N(N_2H^+)$, with a linear correlation coefficient R =-0.7. Starless cores, on average, tend to have a higher $N(CCS)/N(N_2H^+)$ ratio. L1527 has not been reported in Figure 5 because of its peculiar high-C₃H₂ column density, which is also associated with a high uncertainty (see Table 3). The observed variation of the $N(CCS)/N(N_2H^+)$ abundance ratio between 3.2 and 0.3 is well reproduced by "standard pseudo-time-dependent" gas-phase chemical models at cloud ages of ~10⁶ and $\geq 10^7$ yr, respectively (Lee, Bettens, & Herbst 1996). However, such models are not able to reproduce values of $N(C_3H_2)/N(CCS) < 2$ at any time, in contrast with observations.

We point out, however, that the above statements are based on a small sample (see Table 5), especially for starless cores. In fact, two of five starless cores (L1512 and L63) have $N(CCS)/N(N_2H^+) < 1$, and B5:N and L1031B, two objects associated with IRAS sources, have $N(CCS)/N(N_2H^+) > 2$. This may indicate the presence of evolutionary differences between similar cores. Moreover, it has been recently found that carbon-chain molecules attain an abundance peak also at late times $(>10^6 \text{ yr})$ in chemical models where gas-phase depletion onto dust grains is accounted for (Ruffle et al. 1998). Therefore, more detailed comparisons with chemical models as well as estimates of gas depletion are needed to better understand the above results (see also Caselli et al. 1998b).

5.5. N_2H^+ and N_2 Abundances

We use the column densities $N(N_2H^+)$, presented in Table 2, to estimate the typical abundance of N_2H^+ ,



FIG. 5.—Column density ratio $N(C_3H_2)/N(CCS)$ plotted vs. $N(CCS)/N(N_2H^+)$ for starless cores (*empty circles*) and cores with stars (*filled circles*). The straight line is the best fit to all the data in the figure. The linear correlation coefficient is R = -0.7, indicating a good anticorrelation between the two quantities. This may reflect different chemical evolutions between the cores. Starless cores have, on average, higher $N(CCS)/N(N_2H^+)$ ratios. Low values (≤ 1) of the $N(CCS)/N(N_2H^+)$ abundance ratio are representative of young ($\leq 10^6$ yr) clouds.

 $x(N_2H^+)$, in our sample. We assume that the core is a uniform sphere of mean density $n = n(H_2) + n(He)$ and radius R, so that

$$x(N_2 H^+) = \frac{3N(N_2 H^+)}{4n(H_2)R}.$$
 (5)

To evaluate, we adopt $n(H_2) = 2 \times 10^4 \text{ cm}^{-3}$ and R = 0.1 pc taken from the NH₃ analysis and maps of BM, and the mean and standard deviation in column density from Table 2, $\langle N(N_2H^+) \rangle = (6 \pm 4) \times 10^{12} \text{ cm}^{-2}$, yielding $x(N_2H^+) = (7 \pm 4) \times 10^{-10}$. These N₂H⁺ abundances are similar to those obtained

These N_2H^+ abundances are similar to those obtained by Womack et al. (1992a) in the dark cloud cores TMC-1 and L134 N, typically 7×10^{-10} . However, the results presented here apply to a much larger sample of 60 low-mass cores. These results further suggest that the low-mass cores are relatively similar in their abundance of N_2H^+ , within a factor of a few. In contrast, the abundances of N_2H^+ appear more variable in more massive cores. In the Orion molecular ridge, $x(N_2H^+)$ varies by a factor of 10 from the Kleinmann-Low nebula to the "radical ion peak" (Ungerechts et al. 1997).

Considering a simple steady-state chemical network, we can derive the N_2 abundance from our N_2H^+ observations (see also Herbst et al. 1977; Womack et al. 1992b). This is a very important issue, given that (1) N_2 is predicted to be the primary carrier of nitrogen in molecular clouds, and (2) N_2 has no permanent dipole moment and hence possesses no pure rotational spectrum. At steady state, the major route to formation of N_2H^+ in dark clouds is

$$N_2 + H_3^+ \to N_2 H^+ + H_2$$
, (6)

which proceeds at the rate $k_8 = 1.7 \times 10^{-9}$ cm³ s⁻¹ (Lee et al. 1996). N₂H⁺ is primarily destroyed by CO and electrons:

$$N_2H^+ + CO \rightarrow HCO^+ + N_2 , \qquad (7)$$

$$N_2H^+ + e \to N_2 + H \tag{8}$$

The rate coefficients of the two reactions, at T = 10 K, are $k_9 = 1.5 \times 10^{-9}$ cm³ s⁻¹ and $k_{10} = 3.6 \times 10^{-6}$ cm³ s⁻¹, respectively (Lee et al. 1996). At steady state, when CO is abundant, reactions (7) and (8) proceed at a similar rate in spite of the different rate coefficients. The fractional abundance of N₂ [$x(N_2) = n(N_2)/n(H_2)$] is then determined by the steady-state relation for the N₂H⁺ abundance:

$$x(N_2) = \frac{k_9 x(CO) + k_{10} x(e)}{k_8 x(H_3^+)} x(N_2 H^+) .$$
(9)

An analytical expression relating $x(N_2)$ to $x(N_2H^+)$ can be derived from equation (9) after evaluating $x(H_3^+)$ and x(e). The abundance of H_3^+ is found by equating the rate of its formation, which follows the ionization of H_2 , to the destruction rate δ , mainly because of reactions with neutral particles (Dalgarno & Lepp 1984):

$$x(\mathrm{H}_{3}^{+}) = \frac{\zeta}{\delta n(\mathrm{H}_{2})}, \qquad (10)$$

where ζ is the cosmic ray ionization rate. Recent chemical models of dense molecular clouds (e.g., Lee et al. 1996) show that, at steady state, atomic oxygen and CO are the main destruction partners of H_3^+ , and $x(O) \sim x(CO)$. Given that

in molecular clouds most of the carbon is locked up in CO, and adopting the most updated estimate of the gas-phase carbon abundance in the interstellar medium $[n(C)/n_{\rm H} \sim 1.4 \times 10^{-4}$, with $n_{\rm H} = n({\rm H}) + 2n({\rm H}_2)$; Cardelli et al. 1996], equation (10) can be written in the form

$$x(\mathbf{H}_3^+) = 8 \times 10^{11} \frac{\zeta f}{n(\mathbf{H}_2)}, \qquad (11)$$

where f, the "depletion factor," represents the fraction of carbon and oxygen left in the gas phase in dense clouds after adsorption onto dust grains.

The fractional abundance of electrons in dense cloud cores has been recently determined by Caselli et al. (1998b) and Williams et al. (1998), based on observations of HCO^+ and DCO^+ . Here, for simplicity, we use the expression of the electron fraction found by balancing cosmic ray ionization and recombination:

$$x(e) = 3.2 \times 10^3 n(\mathrm{H}_2)^{-1/2} \zeta^{1/2}$$
(12)

(McKee et al. 1993).

Substituting equations (11) and (12) into equation (9), we finally obtain

(**- -**)

$$x(N_2) = 3 \times 10^{-16} \frac{n(H_2)}{\xi} \times \left[\frac{k_9 + 0.04k_{10} fn(H_2)^{-1/2}}{k_8 f^2} \right] x(N_2 H^+), \quad (13)$$

which gives the abundance of N₂ as a function of gas density and depletion factor, once $x(N_2H^+)$ has been observationally determined. Introducing numerical values in equation (13), with $n(H_2) = 2 \times 10^4$ cm⁻³, $x(N_2H^+) =$ $(7 \pm 4) \times 10^{-10}$, and $\zeta = 10^{-17}$ s⁻¹, the N₂ abundance is $x(N_2) = (6 \pm 4) \times 10^{-4}, (2 \pm 1) \times 10^{-4}, (1.3 \pm 0.7) \times 10^{-4},$ $(7 \pm 4) \times 10^{-5}$, and $(3 \pm 2) \times 10^{-5}$ when f = 1, 2, 3, 5, and 10, respectively. A depletion factor of at least 5 is then needed to avoid $x(N_2)$ to overcome the maximum value allowed; i.e., the mean interstellar gas-phase nitrogen abundance $n(N)/n_{\rm H} = 7.5 \times 10^{-5}$ (Meyer, Cardelli, & Sofia 1997). This result is in agreement with chemical models, where f > 5 is requested to reproduce the observed N₂H⁺ abundance and the ratio $x(N_2H^+)/x(N_2)$ calculated with equation (10).

To summarize, the chemistry of N_2H^+ is simple and well reproduced by steady-state models, in analogy with NH_3 and unlike cyanopolyynes, which are better reproduced by pseudo-time-dependent chemical models at "early time" (e.g., Herbst & Leung 1989). However, there is a tendency for N₂ to be more abundant than the steady-state prediction of gas-phase chemical models, especially for undepleted abundances of C and O. This suggests that in dark clouds either (1) all N is in the form of N₂ [whereas gas-phase chemical models predict $x(N) \sim x(N_2)$ at steady state; see Lee et al. 1996], or (2) carbon and oxygen are depleted by at least a factor of 5 with respect to their cosmic values, whereas nitrogen is undepleted. In any case, a significant depletion of N₂ onto dust grains seems unlikely.

6. SUMMARY

We made a survey of $N_2H^+(1-0)$ and $C_3H_2(2_{1,2}-1_{0,1})$ in 59 low-mass cores and $CCS(4_3-3_2)$ in a subsample of 20 objects by using the Haystack 37 m antenna. The detection rate was 94% for N_2H^+ , 84% for C_3H_2 , and 75% for CCS, indicating that the three species are widespread in molecular cloud cores and easy to detect. The main conclusions of this work are the following: (1) Velocities and line widths of the three molecules are well correlated among themselves and with NH₃, indicating a kinematic consistency for the four molecular species. (2) The velocity difference between N_2H^+ and C_3H_2 is very small (<0.03 km s⁻¹), suggesting that ions and neutrals are well coupled. This upper limit on ion-neutral drift is the first experimental indication that relative speeds of ions and neutrals in star-forming dense cores do not significantly exceed those expected for ambipolar diffusion. This limit is not a detection of ambipolar diffusion, but it indicates that no ion-neutral drift process faster than ambipolar diffusion is operating in the typical low-mass dense core. (3) N_2H^+ column densities have been utilized to determine the abundance of the unobservable N_2 molecule. Our results are consistent with nitrogen being all in molecular form and undepleted.

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APPENDIX

CALCULATION OF COLUMN DENSITY

A1. N_2H^+

The N_2H^+ column density has been calculated with the following equation:

$$N(\text{cm}^{-2}) = 3.3 \times 10^{11} \frac{\tau \,\Delta v T_{\text{ex}}}{1 - e^{-4.47/T_{\text{ex}}}},$$
(14)

where τ is the total optical depth, Δv is the intrinsic line width in km s⁻¹, and T_{ex} is the excitation temperature in K. All these quantities can be determined by using the "hyperfine structure (hfs) method" in CLASS; the separation of the seven components has been adopted from Caselli et al. (1995). Numerical values in equation (14) can be derived once the permanent electric dipole moment (μ_{el}), the rest frequency of the line (v_0), and the rotational partition function (Q_{rot}) are known. We

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adopted $\mu_{el} = 3.4$ D (Havenith et al. 1990), $v_0 = 93173.4035$ MHz (Caselli et al. 1995), and $Q_{rot} = kT_{ex}/hB$, where B is the rotational constant. The uncertainty on N has been calculated by propagating the uncertainties on τ , Δv , and T_{ex} .

For those cores where the $N_2H^+(1-0)$ emission is optically thin, we used

$$N(\rm{cm}^{-2}) = 8.0 \times 10^{11} \,\Delta v T_R \,, \tag{15}$$

where $T_{ex} = 5$ K has been assumed. The value T_R is the brightness temperature of the N₂H⁺(1-0) line in K, given by the ratio of the brightness temperature of the main hyperfine component (F_1 , F = 2, $3 \rightarrow 1$, 2) to its statistical weight.

A2. C_3H_2

To calculate the column density of the ortho- C_3H_2 from the $2_{1,2} \rightarrow 1_{0,1}$, equation (2) of Bell et al. (1988) has been used. With the approximated form of the partition function valid for asymmetric top molecules as given by Gordy & Cook (1984) and the expression of the energy level E_I for lightly asymmetric oblate top molecules (Townes & Schawlow 1975), we obtain the following:

$$N(C_{3}H_{2}) = 4.03 \times 10^{11} \frac{\Delta v \tau T_{ex}^{3/2} e^{2.4/T_{ex}}}{1 - e^{-4.1/T_{ex}}}.$$
(16)

The C_3H_2 rotational constants (A = 35.092596 GHz, B = 32.212931 GHz, and C = 16.749315 GHz) have been adopted from Swade (1989), and the dipole moment is $\mu_{el}(C_3H_2) = 3.35 \text{ D}$ (Lee, Bunge, & Schaefer 1985).

As shown in Figure 2, the $2_{1,2} \rightarrow 1_{0,1}$ lines often have asymmetric profiles, suggesting the presence of self-absorption and thus optical depths, which are not negligible. From the single C_3H_2 line, it is not possible to determine τ and T_{ex} simultaneously; we then assumed $T_{\rm ex} = 7$ K and calculated the optical depth from

$$\tau = \ln\left(\frac{T_{\rm ex} - T_R}{T_{\rm ex} - T_R - T_{\rm bb}}\right),\tag{17}$$

where $T_{bb} = 2.7$ K is the cosmic background temperature. The assumed T_{ex} value is the smallest integer value, which satisfies the relation $T_{ex} > T_R - T_{bb}$ for all the cores in our sample. Moreover, our choice is consistent with the multitransition study of C_3H_2 toward TMC-1 by Gerin et al. (1987), which yields a rotational temperature $T_{rot} \sim 7$ K. There is the possibility that some of the cores have $T_{ex} \sim 5$ K (e.g., L1544; Gerin et al. 1987). In these cases, the assumption of $T_{ex} = 7$ K may underestimate the C_3H_2 column density by a factor of about 2, if $T_R \sim 2 \text{ K}$ (for $T_R < 2$, the difference becomes negligible; on the other hand, when $T_R > 2.3 \text{ K}$, eq. [17] requires $T_{ex} > 5 \text{ K}$). The comparison with Cox et al. (1989) C_3H_2 observations in the nine cores we have in common leads to $N(C_3H_2)_{Cox} \simeq (2 \pm 1) \times N(C_3H_2)_{thiswork}$, in agreement with the previous statement.

A3. CCS

Assuming the Boltzmann population distribution with temperature T_{ex} , the CCS column density can be determined from the $J_N = 4_3 \rightarrow 3_2$ transition with the expression

$$N(\text{CCS}) = 8.7 \times 10^{11} \frac{\tau \Delta v T_{\text{ex}}}{(1 - e^{-2.2/T_{\text{ex}}})e^{-3.7/T_{\text{ex}}}},$$
(18)

where the following constants have been introduced: the dipole moment $\mu_{el} = 2.81$ D (Murakami 1990); the transition frequency v = 45379.033 MHz (Yamamoto et al. 1990); and the rotational constant B = 6477.75036 MHz (Yamamoto et al. 1990). As in the case of N_2H^+ , the partition function for linear molecules has been assumed.

Similarly to the $C_3H_2(2_{1,2}-1_{0,1})$ transition, both the optical depth *and* the excitation temperature relative to the CCS line cannot be deduced. We assumed $T_{ex} = 6$ K for the same reasons explained in § 5.4.2. SYO found $T_{ex} = 5$ K in a sample of low-mass cores. However, in our sample, the high brightness temperature observed toward L1498 requires at least $T_{ex} = 6$ K to satisfy equation (17).

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