1. INTRODUCTION

In the cold and dense interiors of starless cores, chemical evolution is expected to proceed at a relatively slow pace due to the low temperatures and densities. However, as the cores collapse and transition towards protostellar status, increased temperatures and densities facilitate the formation of new molecules and the generation of protostars. In this study, we present a survey of HCO+(3–2) observations towards dense cores with previous measurements of \( \text{N}_2\text{D}^+/(\text{N}_2\text{H}^+) \) to explore the correlation between deuteron fractionation and protostellar activity. The properties of these cores, such as mass, temperature, and non-thermal motions, are expected to evolve as they transition from being starless to forming a protostar.

We observe the HCO+(3–2) line in the HCO+ (3–2) and H13CO+ (3–2) transitions to probe the infall and outflow motions in dense cores. The observed line becomes optically thick in the inner part of the core, allowing us to determine the infall velocity. Various models have been developed to predict the infall velocity in idealized cases, but in real cores, the infall velocity depends on the size of the core, the gas temperature, and the thermal and non-thermal motions. In this survey, we compare the observed infall velocities with those predicted by theoretical models to assess the impact of protostellar activity on the core dynamics.

We find that the cores with the highest degree of deuteration, as indicated by the \( \text{N}_2\text{D}^+/(\text{N}_2\text{H}^+) \) ratio, are more likely to have significant protostellar activity. The cores with higher ratios exhibit more significant infall motions, suggesting that protostellar activity is driving these motions.

In conclusion, our study provides insights into the correlation between deuteron fractionation and protostellar activity in dense cores. The observed infall velocities are consistent with theoretical predictions, highlighting the importance of protostellar activity in shaping the dynamical properties of these cores.
cores with the highest \(N(N_2D^+)/N(N_2H^+))\) ratio are really on the verge of forming a protostar, then we expect them to also show infall signatures. Those cores with smaller observed deuterium enrichment would have slower, or non-existent, infall motions.

Similarly, those cores more massive than their thermal Jeans mass might also be expected to exhibit infall motions. We also compare the observed motions with the Jeans stability of each core to test the hypothesis that those cores with \(M/M_J > 1\) will have inward motions while cores with \(M/M_J < 1\) will appear to be static. More details on this survey are reported below.

### 2. OBSERVATIONS

The 26 dense cores in this survey are those for which the \(N(N_2D^+)/N(N_2H^+))\) ratios were measured by Crapsi et al. (2005). The Crapsi et al. (2005) sample is meant to be representative of evolved (i.e., dense) starless cores, with their high densities derived from \(N_2H^+\) (1–0) or 1.2 mm dust continuum emission. Although thought to be starless by Crapsi et al. (2005), the cores L1521F (Bourke et al. 2006) and L328 (Lee et al. 2009) were later found to be protostellar. The Crapsi et al. (2005) cores are nearby, i.e., within 250 pc, making them comparatively easy to study. We chose to observe HCO\(^+\) (3–2) to trace inward and outward motions in these dense cores. HCO\(^+\) (3–2) was shown by Gregersen & Evans (2000) to be a good tracer of line asymmetries in starless cores. The effective critical density of HCO\(^+\) (3–2), \(6.3 \times 10^8\) cm\(^{-3}\) (Evans 1999), is well-matched to the densities of the cores in the Crapsi et al. (2005) sample, 8 \(\times 10^3\) cm\(^{-3}\) to 1.4 \(\times 10^6\) cm\(^{-3}\). The observed spectra are likely to be affected by optical depth and depletion such that HCO\(^+\) (3–2) may not be tracing exactly the same portion of every core in our sample. Although this source of uncertainty is unavoidable in a survey such as ours, we outline a possible path around this uncertainty in Section 5.

Our observations were centered on the position of the peak \(N(N_2D^+)/N(N_2H^+))\) given in Crapsi et al. (2005). The \([N_2D^+] /[N_2H^+]\) ratio is expected to peak in the region with the highest density and coldest temperature. High densities and low temperatures (and therefore low thermal support) are conditions that are likely to lead to gravitational collapse. The coordinates of our pointed observations and the degree of deuterium enrichment are given in Tables 1 and 2. The noise values of the spectra are given in Table 1. The observed HCO\(^+\) (3–2) spectra are shown in Figures 1(a)–(d).

The data were obtained at the James Clerk Maxwell Telescope\(^7\) (JCMT) using the 1 mm Receiver RXA3 front-end and the ACSIS backend throughout semesters 10A and 10B. Each core was observed in position-switching mode with an off-position located (\(\sim 300, –300\)) arcsec (in the J2000 coordinate frame) from the core position (see Table 1). ACSIS was configured to cover two 250 MHz wide windows, one centered on HCO\(^+\) (3–2) at 267.558 GHz and another centered on 180 GHz.

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\(^{7}\) The James Clerk Maxwell Telescope is operated by the Joint Astronomy Centre on behalf of the Science and Technology Facilities Council of the UK, the Netherlands Association for Scientific Research, and the National Research Council of Canada.

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| Name   | R.A.\(^5\) (J2000) | Decl.\(^5\) (J2000) | Peak Intensity \(T_{mb}\) (K) | Integrated Intensity \(T_{mb}\) (K km s\(^{-1}\)) | Velocity Dispersion (km s\(^{-1}\)) | rms (K) |
|--------|--------------------|---------------------|-------------------------------|---------------------------------|---------------------------------|--------|
| L1498  | 04:10:51.5         | +25:09:58           | 0.57                          | 0.34                            | 0.24                            | 0.08   |
| L1495  | 04:14:11.2         | +28:08:56           | 1.00                          | 0.58                            | 0.22                            | 0.11   |
| L1495B | 04:18:05.1         | +28:22:22           | 0.93                          | 0.57                            | 0.22                            | 0.09   |
| L1495A | 04:18:41.8         | +28:23:50           | N/A                           | N/A                             | N/A                             | N/A    |
| L1521F | 04:28:39.1         | +26:51:35           | 2.91                          | 2.73                            | 0.19                            | 0.10   |
| L1400A | 04:30:56.8         | +54:52:36           | 0.49                          | 0.19                            | 0.15                            | 0.14   |
| TMC 2  | 04:32:48.7         | +24:25:52           | 1.59                          | 0.71                            | 0.11                            | 0.11   |
| TMC 1  | 04:41:32.9         | +25:44:44           | 1.39                          | 0.61                            | 0.09                            | 0.11   |
| TMC 1C | 04:41:38.8         | +26:00:22           | 0.40                          | 0.30                            | 0.29                            | 0.11   |
| L1507A | 04:42:38.6         | +29:43:45           | 1.10                          | 0.37                            | 0.08                            | 0.08   |
| CB 23  | 04:43:27.7         | +29:39:11           | 0.92                          | 0.26                            | 0.07                            | 0.07   |
| L1517B | 04:55:17.6         | +30:37:49           | 1.19                          | 0.35                            | 0.12                            | 0.09   |
| L1512  | 05:04:09.7         | +32:43:09           | 0.68                          | 0.22                            | 0.09                            | 0.10   |
| L1544  | 05:04:16.6         | +25:10:48           | 1.66                          | 0.61                            | 0.12                            | 0.08   |
| L183   | 15:54:08.4         | –02:52:33           | 0.35                          | 0.34                            | 0.38                            | 0.06   |
| Oph D  | 16:28:28.9         | –24:19:19           | 1.90                          | 1.29                            | 0.17                            | 0.06   |
| L1689B | 16:34:45.8         | –24:37:50           | 1.06                          | 1.04                            | 0.40                            | 0.16   |
| L234E-S| 16:48:08.6         | –10:57:25           | 1.13                          | 0.59                            | 0.14                            | 0.09   |
| B68    | 17:22:39.8         | –23:49:46           | 0.49                          | 0.26                            | 0.21                            | 0.09   |
| L492   | 18:15:47.4         | –03:45:53           | 1.29                          | 0.84                            | 0.26                            | 0.13   |
| L328\(^d\) | 18:17:00.4   | –18:01:52           | 1.65                          | 1.43                            | 0.22                            | 0.09   |
| L429   | 18:17:50.1         | –08:13:40           | 1.94                          | 1.30                            | 0.19                            | 0.10   |
| L694-2 | 19:41:04.5         | +10:57:02           | 1.72                          | 0.63                            | 0.10                            | 0.10   |
| L1197  | 22:37:02.3         | +58:57:21           | 1.38                          | 0.46                            | 0.09                            | 0.10   |
| CB 246 | 23:56:41.5         | +58:34:09           | 1.00                          | 0.44                            | 0.10                            | 0.07   |

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**Notes.**

\(^{5}\) Name and coordinates from Lee & Myers (1999), not to be confused with LDN 1495B with J2000 coordinates 04:15:36.5 +28:46:06.

\(^{b}\) Protostellar (Bourke et al. 2006).

\(^{d}\) Protostellar (Lee et al. 2009).
H$_{13}$CO$^+$ (3–2) at 260.255 GHz. Each window was divided into 8192 channels for a resolution of $\sim 0.05$ km s$^{-1}$. Each core was observed for about 45 minutes of integration and the beam size of the observations was $\sim 20''$ FWHM. The JCMT beam size is fairly well matched to the beam sizes of the $N_2D^+$ (2–1) observations presented in Crapsi et al. (2005), i.e., $\sim 16''$ and $\sim 20''$ FWHM, respectively.

After acquisition, the data were reduced using the Starlink package. Each integration was first visually checked for baseline ripples and extremely large spikes, and such data were removed from the ensemble, if necessary. Spectral baselines were subtracted, frequency axes converted to velocities, and spectra trimmed using Starlink scripts kindly provided by T. van Kempen. The integrations were visually inspected and written out as FITS format files using other standard Starlink routines. Spectra for each core were co-added outside of Starlink, using the IDL programming language. Spectra were converted to main beam brightness temperatures using an assumed efficiency of 0.75. HCO$^+$ (3–2) emission was detected toward each core except for L1495A-S, but H$_{13}$CO$^+$ (3–2) emission was only detected toward a few cores (L1521F, Oph D, L1689B, and L328; see Figures 1(a)–(d)). Hence, the H$_{13}$CO$^+$ data will not be discussed further in this paper.

### Notes.

| Name     | Distance (pc) | $N$(N$_2$D$^+$/N(N$_2$H$^+$)$^a$ | $L_{bol}$ (L$_{⊙}$) | $M_L$ (M$_{⊙}$) | $M_J$ (M$_{⊙}$) | $M/M_J$ |
|----------|---------------|-------------------------------|---------------------|-----------------|---------------|---------|
| L1498    | 140$^a$       | 0.04 ± 0.01                   | 56.0$^b$            | 0.038           | 0.8$^b$       | 1.0     |
| L1495    | 140$^a$       | 0.05 ± 0.01                   | 92.8$^d$           | 0.063           | 4.2$^d$       | 1.7     |
| L1495B   | 140$^a$       | 0.10 ± 0.04                   | 15.5$^b$           | 0.010           | 0.1$^b$       | 0.3     |
| L1495A-N | 140$^a$       | 0.04 ± 0.01                   | 20.9$^b$           | 0.014           | 0.7$^b$       | 0.4     |
| L1495A-S | 140$^a$       | 0.08 ± 0.03                   | 83.0$^b$           | 0.056           | 4.4$^b$       | 1.5     |
| L1521F   | 140$^a$       | 0.10 ± 0.02                   | 230.6$^i$          | 0.156           | 8.2$^f$       | 4.2     |
| L1507A   | 140$^a$       | 0.11 ± 0.02                   | 31.9$^b$           | 0.022           | 0.2$^b$       | 0.6     |
| TMC 2    | 140$^a$       | 0.04 ± 0.01                   | 45.2$^b$           | 0.031           | 0.4$^b$       | 0.8     |
| TMC 1C   | 140$^a$       | 0.07 ± 0.02                   | 87.1$^b$           | 0.059           | 3.7$^b$       | 1.6     |
| TMC 1    | 140$^a$       | 0.05 ± 0.01                   | 70.0$^e$           | 0.053           | 2.5$^e$       | 1.4     |
| L1517B   | 140$^a$       | 0.06 ± 0.01                   | 71.7$^b$           | 0.052           | 1.6$^b$       | 1.4     |
| L1512    | 140$^a$       | 0.05 ± 0.01                   | 47.5$^b$           | 0.032           | 0.5$^b$       | 0.9     |
| L1544    | 140$^a$       | 0.23 ± 0.04                   | 60.1$^b$           | 0.041           | 1.8$^b$       | 1.6     |
| L183     | 165$^a$       | 0.22 ± 0.04                   | 71.3$^b$           | 0.057           | 4.3$^b$       | 1.6     |
| Oph D    | 165$^a$       | 0.44 ± 0.08                   | 55.3$^b$           | 0.055           | 1.9$^b$       | 1.2     |
| L1689B   | 165$^a$       | 0.09 ± 0.04                   | 78.4$^b$           | 0.063           | 5.4$^b$       | 1.7     |
| L234E-S  | 165$^a$       | 0.08 ± 0.02                   | 27.8$^b$           | 0.022           | 0.4$^b$       | 0.6     |
| B68      | 125$^a$       | 0.03 ± 0.01                   | 57.5$^b$           | 0.035           | 0.7$^b$       | 1.0     |
| L492     | 200$^a$       | 0.05 ± 0.01                   | 161.1$^f$          | 0.156           | 5.2$^f$       | 4.2     |
| L328     | 200$^a$       | 0.07 ± 0.01                   | 31.7$^b$           | 0.031           | 1.2$^b$       | 0.8     |
| L429     | 200$^a$       | 0.28 ± 0.05                   | 19.4$^b$           | 0.019           | 0.7$^b$       | 0.5     |
| L694-2   | 250$^a$       | 0.26 ± 0.05                   | 66.4$^b$           | 0.080           | 6.8$^b$       | 2.2     |
| L1197    | 140$^b$       | 0.07 ± 0.03                   | 19.1$^b$           | 0.013           | 0.3$^b$       | 0.8     |
| CB 246   | 140$^a$       | 0.03 ± 0.01                   | 27.9$^b$           | 0.019           | 0.2$^b$       | 0.5     |

### 3. RESULTS

The HCO$^+$ spectra were fit with a Gaussian model as well as two simple infall/outflow models, the “two-layer” model from Myers et al. (1996) and the “HILL5” model from De Vries & Myers (2005). The two-layer model describes the case of two regions with differing excitation temperatures (lower for the front, higher for the rear) and identical velocity dispersions and total optical depth. The HILL5 model describes the case of a core whose excitation temperature peaks at the center and falls off linearly with radius. The HILL5 core also has its front and rear halves moving toward or away from each other. Both models reproduce spectra with one peak and a shoulder reasonably well, though the HILL5 model is better than the two-layer model at fitting spectra with two peaks (De Vries & Myers 2005). The five free parameters in both infall/outflow models are inward/outward velocity, kinetic temperature, peak optical depth, velocity dispersion, and velocity with respect to the local standard of rest. The dynamic models assume that the two peaks in the prototypical infall/outflow profile arise from self-absorption and not from having two unrelated sources with slightly different velocities along the same line of sight. This assumption can be tested through observations of an optically thin tracer that should peak at the same velocity as the self-absorption dip in the optically thick spectrum if no radial

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8 http://www.jach.hawaii.edu/JCMT/spectral_line/Standards/beameff.html
Figure 1. (a) Observed HCO\(^+\) (3–2) spectra (black) and H\(^{13}\)CO\(^+\) (3–2) spectra (gray) for the cores L1498, L1495, L1495B, L1495A-N, L1495A-S, and L1521F. The dotted vertical line shows the LSR velocities of N\(_2\)H\(^+\) (1–0) (Crapsi et al. 2005). The H\(^{13}\)CO\(^+\) spectra are offset by \(-0.5\) K, with a dashed horizontal line showing the zero level of the H\(^{13}\)CO\(^+\) spectra. The red dotted lines show the best fit to the observed HCO\(^+\) (3–2) spectra. (b) Same as (a), for the cores L1400A, TMC2, TMC1, TMC1C, L1507A, and CB23. (c) Same as (a), for the cores L1517B, L1512, L1544, L183, Oph D, and L1689B. (d) Same as (a), for the cores L234E-S, B68, L492, L328, L429, L694-2, L1197, and CB 246.

(A color version of this figure is available in the online journal.)

motion is present. The H\(^{13}\)CO\(^+\) (3–2) observations described in Section 2 were intended to be this optically thin tracer, but detections were rare. The N\(_2\)H\(^+\) and N\(_2\)D\(^+\) observations presented in Crapsi et al. (2005) are sufficient to show that there are no confounding superpositions in our sample. In the relatively few cases where H\(^{13}\)CO\(^+\) (3–2) is detected, the line peaks at the same velocity as the N\(_2\)H\(^+\) and N\(_2\)D\(^+\) spectra. The Gaussian and dynamic models were fit with the MPFIT suite of functions (Markwardt 2009).

For each core, the Gaussian and dynamic model fits were compared with \(F\)-tests, taking into account the \(\chi^2\) values for the fits and the degrees of freedom in the fits. For those cores where the \(F\)-test prefers a dynamic model and the inward/outward motions are at least three times the uncertainty of the motion, we treat the core as having inward or outward motions for the rest of this paper. We describe as “static core” those cores for which the \(F\)-test prefers the Gaussian model or the uncertainty in the radial motions is greater than three times the magnitude of the motion. The signal-to-noise ratio of the L1495A-S observations is too low to attempt a fit to either model. The peak intensities, integrated intensities, and velocity dispersions (standard deviations, or \(\sigma\) for a Gaussian velocity distribution) measured from the best fits to the HCO\(^+\) spectra are given in Table 1, with the intensities given on \(T_{mb}\) scale. Note that the cores L1521F and L328 are actually protostellar, not starless, and L1521F has the largest infall velocity in...
our survey. The infall velocity of L1521F was measured to be 0.2–0.3 km s\(^{-1}\) by Onishi et al. (1999). The presence of an embedded protostar likely reduces the accuracy of the HILL5 and two-layer models (note the relatively poor fit to the blue peak of the spectrum), so we trust the detailed model of Onishi et al. (1999) to provide a more accurate estimate of the infall velocity than we derive here. The kinematic state and preferred model of each core as determined by the model fits are given in Table 3, along with previous kinematic classifications from the literature (see Section 4). In Table 3, we also give the velocity with respect to the local standard of rest from the best-fit model to our HCO\(^+\) spectra, along with the LSR velocity fit to the N\(_2\)H\(^+\) (1–0) spectra from Crapsi et al. (2005). We find that the median of the absolute value of the velocity difference between the LSR velocity from HCO\(^+\) and N\(_2\)H\(^+\) is 0.07 km s\(^{-1}\) with a standard deviation of 0.1 km s\(^{-1}\). This velocity difference likely comes from velocity gradients along the line of sight due to inward/outward motions, since HCO\(^+\) and N\(_2\)H\(^+\) will sometimes probe different layers within a core. The uncertainties given in Table 3 are the 1\(\sigma\) standard deviations.

Masses and radii for the cores in this survey were taken from the literature and calculated from (sub)millimeter continuum surveys. Most core masses are derived from the observed flux at 850 \(\mu\)m or 1.2 mm using the formula

\[
M = 0.12 \left[ e\left(\frac{\lambda}{\lambda_{\text{mm}}} \frac{\nu}{\nu_{\text{mm}}}^{-1} - 1\right) \frac{\kappa_{\nu}}{0.01 \text{ cm}^2 \text{ g}^{-1}} \right]^{-1} \left(\frac{S_{\nu}}{\text{Jy}}\right) \times \left(\frac{D}{100 \text{ pc}}\right)^2 \left(\frac{\lambda}{\text{mm}}\right)^3 M_{\odot},
\]

(1)

We assume that all cores are isothermal at 10 K, as assumed in the core mass calculations of Crapsi et al. (2005) and consistent with the average temperatures derived from NH\(_3\) observations of starless cores (Tafalla et al. 2002; Schnee et al. 2009).
Real cores have temperature gradients ranging from $\sim 13$ K at large radii to $\sim 6$ K at the center (e.g., Crapsi et al. 2007; Pagani et al. 2007; Schnee et al. 2007b), but these variations in temperature do not affect the conclusions of this paper. We assume a value of $\kappa_\nu$ at 850 $\mu$m of 0.01 cm$^2$ g$^{-1}$ and $\kappa_\nu$ at 1.2 mm of 0.005 cm$^2$ g$^{-1}$, as assumed in Sadavoy et al. (2010) and Crapsi et al. (2005), respectively. These values for $\kappa_\nu$ are consistent with each other for an emissivity spectral index of 2, in agreement with observations of the starless cores L1498 (Shirley et al. 2005) and TMC-1C (Schnee et al. 2010). Distances ($D$) to the cores and references used to determine core masses are given in Table 2. We were unable to find previously published values for the masses and radii of the cores L1495 and L1400A.

Following Sadavoy et al. (2010), we calculate the Jeans mass for the cores in this survey using the formula

$$M_J = 1.9 \left( \frac{T}{10 \text{ K}} \right) \left( \frac{R}{0.07 \text{ pc}} \right) M_\odot.$$  

As in the calculation of core masses, when calculating the Jeans mass, we assume that all cores are isothermal at $T = 10$ K and use the radii ($R$) given in Table 2.

4. DISCUSSION

A plot of infall velocity (see Table 3) versus degree of deuteration (see Table 2) is shown in Figure 2. Nine cores show no evidence for infall or outflow, 5 cores have outward motions, and 11 have inward motions. Below an $N(N_2D^+)/N(N_2H^+)$ ratio of 0.1, there is no correlation with infall velocity. For the eight cores with $N(N_2D^+)/N(N_2H^+) \geq 0.1$, six cores have infall velocities and two cores appear to be static. We therefore find a general trend, though not a quantitative correlation, that inward motions are more likely to be found at higher levels of deuteration, whereas at lower levels of deuteration, inward and outward motions are roughly equally likely to be found. The HCO$^+$ spectra therefore support the idea that
Simpson et al. (2011) found that the Jeans stability of a pre-stellar core provides a reasonable predictor of its dynamical state. As shown in Figure 2 (see also Tables 2 and 3), we find that three Jeans-stable cores (those with $M/M_{\text{Jeans}} < 1$) show inward motions, two cores appear to be static, and four show outflow motions. Those cores with $M/M_{\text{Jeans}} > 1$ are much more likely to have line asymmetries associated with infall (eight cores) than outward motions (no cores), and six cores with $M/M_{\text{Jeans}} > 1$ are best fit by Gaussian profiles. Our results are in agreement with those of Simpson et al. (2011), in that the Jeans stability of dense cores is a useful indicator of likely infall candidates, and the identification of collapsing cores becomes more likely with increasing $M/M_{\text{Jeans}}$. As shown in Figure 2, those cores with $N(N_2D^+)/N(N_2H^+) > 0.1$ also have $M/M_{\text{Jeans}} > 1$.

Many cores with lower degrees of deuteration, however, also have high $M/M_{\text{Jeans}}$ (L1495A-S, TMC-1C, CB 23, L1517B, L1689B, L492, and L328) and these cores sometimes exhibit infall motions that are a consequence of their Jeans instability. There are no cores with $M/M_{\text{Jeans}} < 1$ and $N(N_2D^+)/N(N_2H^+) > 0.1$. Those cores with $M/M_{\text{Jeans}} > 1$, but no indication of inward motions, may be supported by mechanisms other than thermal pressure (e.g., turbulent or magnetic pressure). Alternatively, infall may indeed be on-going, but the signature of this motion could be missing from the HCO$^+$ (3–2) spectra in some cores due to freeze-out (Roberts et al. 2010) or rotation (Redman et al. 2004). We suggest that those cores with super-Jeans masses but no indication for infall are a good sample for future observations.

The origin of outward motions in five starless cores in our survey, as indicated by negative infall velocities in Table 3 and Figure 2, is not fully understood. Such outward motions...
have been seen in previous surveys (e.g., Sohn et al. 2007; Lee & Myers 2011) and may indicate oscillatory behavior (Lada et al. 2003; Broderick & Keto 2010). Indeed, oscillatory behavior may also be responsible for some of the inward motions observed in our HCO$^+$ survey. Smoothed particle hydrodynamics simulations of nominally super-Jeans cores modeled as Bonnor–Ebert spheres may oscillate rather than collapse if the exterior temperatures of the cores are high enough (Anathpindika & Di Francesco 2013). As the sometimes-different classifications of cores as “expanding,” “oscillating,” or “contracting” in Table 3 make clear, observing cores at slightly different positions with different molecular tracers can lead to very different conclusions, an effect which surely adds considerable scatter to plots like Figure 2.

Only 3 of the 16 cores included in 4 surveys of inward and outward motions (Crapsi et al. 2005; Sohn et al. 2007; Lee & Myers 2011, this work) showed the same behavior in all cases (L1544, L694-2, and L1197, which all show inward motions). Infall in the cores L1544 and L694-2 has been particularly well-studied, with evidence for extended infall at speeds $\leq 0.1$ km s$^{-1}$ seen in N$_2$H$^+$ observations (Tafalla et al. 1998; Williams et al. 2006; Keto & Caselli 2010). The lack of a 1:1 correlation between infall velocity and high $N$(N$_2$D$^+$/N(N$_2$H$^+$)) or $M/M_{\text{Jans}}$ is likely to be at least partly a result of the uncertainties in measuring the dynamics of cores with a single molecular tracer at a single position. In addition, because starless cores will not all reach exactly the same level of $N$(N$_2$D$^+$/N(N$_2$H$^+$)) before collapse, one would not expect a perfect correlation with infall even in a comprehensive set of observations. It may seem surprising that some cores in this survey have significant infall velocities without having similarly large $N$(N$_2$D$^+$/N(N$_2$H$^+$)) ratios. As mentioned above, in some cases, the inward motions may be due to oscillations in a stable core rather than being caused by collapse, in which case the low $N$(N$_2$D$^+$/N(N$_2$H$^+$)) ratio is a true indicator of the stability of a core. Alternatively, HCO$^+$ may be preferentially tracing accretion motions instead of contraction or expansion motions of the core itself, as HCO$^+$ is also very abundant at low densities (i.e., in the core envelope and the surrounding molecular cloud), unlike N$_2$H$^+$. For example, molecular abundances in the contracting core TMC-1C are affected by accretion from its environment, from which it is gaining material rich in N$_2$H$^+$ but likely not in N$_2$D$^+$ (Schnee & Goodman 2005; Schnee et al. 2007a). It is also possible that cores with significant infall velocities but low levels of deuterium fractionation are too young to have significant deuterium enrichment despite their high central...
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Figure 2. Infall velocity plotted against the $N(N_2D^+)/N(N_2H^+)$ from Crapsi et al. (2005) (top) and the ratio of the core mass to the thermal Jeans mass, as calculated from Equations (1) and (2) and reported in Table 2 (middle). Positive values of $V_{\text{infall}}$ indicate inward motions. The $N(N_2D^+)/N(N_2H^+)$ ratio against the $M/M_J$ ratio is plotted in the bottom panel. The protostellar cores L328 and L1521F are represented by the gray 'x' symbols and all of the other cores are thought to be starless. “Static cores” are given an infall/outflow velocity of 0 km s$^{-1}$ with no uncertainty and are represented by the triangles. The cores L1495 and L1400A are not plotted in the middle and bottom panels because we could not determine $M/M_J$ for them from the literature. The core L1495A-S is not plotted in any panel because we did not detect it in our HCO$^+$ observations.

Figure 3. D/H ratio plotted against the ratio of the core mass to the thermal Jeans mass, as calculated from Equations (1) and (2) and reported in Table 2 (middle). Positive values of $V_{\text{infall}}$ indicate inward motions. The $N(N_2D^+)/N(N_2H^+)$ ratio against the $M/M_J$ ratio is plotted in the bottom panel. The protostellar cores L328 and L1521F are represented by the gray 'x' symbols and all of the other cores are thought to be starless. “Static cores” are given an infall/outflow velocity of 0 km s$^{-1}$ with no uncertainty and are represented by the triangles. The cores L1495 and L1400A are not plotted in the middle and bottom panels because we could not determine $M/M_J$ for them from the literature. The core L1495A-S is not plotted in any panel because we did not detect it in our HCO$^+$ observations.

5. FUTURE WORK

As outlined in this paper, there is a need for a uniform multidimensional study of the kinematics and chemistry of dense cores. The work presented in this paper is limited by the single-pointing observations. Spectral line maps would be better able to determine the location of peak infall or outflow, and to determine whether a core shows infall or outflow spectral signatures consistently across its extent. Part of the difference between the infall surveys presented in Table 3 can be attributed to the different pointing centers of the observations. To the extent that the velocity field changes across a core, these positional differences will confuse the conclusions of pointed surveys. Furthermore, the “center” of a core is not always a well-defined location. For example the center of L183 is offset by $\sim 20''$ between the studies of Crapsi et al. (2005) and Pagani et al. (2007). A second conclusion that can be drawn from Table 3 is that there is no single best molecular tracer of inward and outward motions in dense cores. Although HCO$^+$ is relatively bright and shows infall motion clearly in many cores, it may not trace the regions in starless cores with the lowest temperatures, highest densities, and most depletion. In this case, the infall velocity measured from HCO$^+$ spectra is likely to be an underestimate of the maximum infall speed. To map precisely the inward and/or outward motions in a core, one would want to have several spectral maps with different molecules and rotational transitions. These observations could then be modeled with a radiative transfer code to constrain self-consistently the density, temperature, chemistry, and kinematic profiles of the cores. Such a survey would require a substantial amount of observing time. We note that the pointed observations of a single infall tracer in this paper required over 30 hr of telescope time (including overheads) over multiple semesters with the JCMT. The combination of high sensitivity with high spatial and spectral resolution provided by the Atacama Large Millimeter/submillimeter Array may make it possible to carry out a comprehensive survey of the connection between the chemistry, kinematics, and role of environment in dense cores.

6. SUMMARY

Crapsi et al. (2005) predicted that dense cores with $N(N_2D^+)/N(N_2H^+) > 0.1$ will show evidence for infall. To test this hypothesis, we observed HCO$^+$ (3–2) toward the Crapsi et al. (2005) sample of 26 dense cores (24 starless and 2 protostellar) and analyzed the spectra to look for inward and outward motions. We find that those cores with the largest values of $N(N_2D^+)/N(N_2H^+)$ and $M/M_{\text{Jeans}}$ are indeed more likely to show the signature of infall than the population as a whole, though some cores that have lower levels of deuterium fractionation and greater Jeans stability also show inward motions.
Since asymmetries from inward and outward motions vary by position within cores (Lee et al. 2001; Lada et al. 2003) and vary by tracer observed (e.g., Lee & Myers 2011), it is not surprising that we do not see very tight correlations between the degree of deuterium fractionation or Jeans stability with infall velocity. The presence of outward motions, and perhaps some of the inward motions, in these presumably long-lived cores is possibly a result of oscillations (Lada et al. 2003; Broderick & Keto 2010; Anathpindika & Di Francesco 2013) and such outward motions have been seen before in previous surveys of dense cores (e.g., Sohn et al. 2007; Lee & Myers 2011). The magnitudes of the inward and outward motions are on the order of the sound speed, suggesting that the cores formed near hydrostatic equilibrium rather than out of supersonic flows.

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