DEUTERIUM FRACTIONATION AS AN EVOLUTIONARY PROBE IN MASSIVE PROTOSTELLAR/CLUSTER CORES

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ABSTRACT

Clouds of high infrared extinction are promising sites of massive star/cluster formation. A large number of cloud cores discovered in recent years allow for the investigation of a possible evolutionary sequence among cores in early phases. We have conducted a survey of deuterium fractionation toward 15 dense cores in various evolutionary stages, from high-mass starless cores to ultracompact H\textsc{ii} regions, in the massive star-forming clouds of high extinction, G34.43+0.24, IRAS 18151−1208, and IRAS 18223−1243, with the Submillimeter Telescope. Spectra of N$_2$H$^+$ (3−2), N$_2$D$^+$ (3−2), and Cl$^{18}\text{O}$ (2−1) were observed to derive the deuterium fractionation of N$_2$H$^+$, $D_{\text{frac}} \equiv N(\text{N}_2\text{D}^+)/N(\text{N}_2\text{H}^+)$, as well as the CO depletion factor for every selected core. Our results show a decreasing trend in $D_{\text{frac}}$ with both gas temperature and line width. Since colder and quiescent gas is likely to be associated with less evolved cores, larger $D_{\text{frac}}$ appears to correlate with early phases of core evolution. Such decreasing trend resembles the behavior of $D_{\text{frac}}$ in the low-mass protostellar cores and is consistent with several earlier studies in high-mass protostellar cores. We also find a moderate increasing trend of $D_{\text{frac}}$ with the CO depletion factor, suggesting that sublimation of ice mantles alters the competition in the chemical reactions and reduces $D_{\text{frac}}$. Our findings suggest a general chemical behavior of deuterated species in both low- and high-mass protostellar candidates at early stages. In addition, upper limits to the ionization degree are estimated to be within 2 × 10$^{-7}$ and 5 × 10$^{-6}$. The four quiescent cores have marginal field-neutral coupling and perhaps favor turbulent cooling flows.

Key words: ISM: abundances – ISM: clouds – ISM: individual objects (G34.43+0.24, IRAS 18151−1208, IRAS 18223−1243) – stars: formation

Online-only material: color figure

1. INTRODUCTION

Clouds of high infrared (IR) extinction, such as infrared dark clouds (IRDCs), are discovered through silhouette against the bright, diffuse IR background emission of the Galactic plane (Egan et al. 1998; Rathborne et al. 2006; Rygl et al. 2010). Because of their cold ($T \lesssim 20$ K), dense ($n_{\text{HI}} \gtrsim 10^4$ cm$^{-3}$), and massive ($M \gtrsim 10^4$ M$_\odot$) nature, IRDCs are thought to be promising sites of massive star/cluster formation. They often harbor cores in a sequence of evolutionary stages (Beuther & Sridharan 2007; Beuther et al. 2010), from fairly quiescent high-mass starless cores (HMSCs; Sridharan et al. 2005; Beuther & Sridharan 2007), followed by cores with accreting low/intermediate-mass protostars/clusters (Beuther & Steinacker 2007; Wang et al. 2011), to high-mass protostellar objects (HMPOs; Sridharan et al. 2002; Beuther et al. 2002a), and even to ultracompact H\textsc{ii} (UC H\textsc{ii}) regions (Battersby et al. 2010). In recent years, a large number of massive cloud cores ($M \gtrsim 10^5$ M$_\odot$) have been identified in IRDCs (Peretto & Fuller 2010) and enable the investigation of possible evolutionary sequence among cores in early phases (Chambers et al. 2009; Battersby et al. 2010; Henning et al. 2010). In general, the strategy to probe evolutionary stages usually involves several indicators, each of which traces some star-forming activities, e.g., radio emission for ionization, gas or dust temperature for internal heating, molecular line width for turbulence, asymmetry of line profiles for infall motions, or high-velocity gas for outflows (e.g., Crapsi et al. 2005; Battersby et al. 2010). In our previous study of G28.34+0.06, we found a moderate decreasing trend in the deuterium fractionation of N$_2$H$^+$, $D_{\text{frac}} \equiv N(\text{N}_2\text{D}^+)/N(\text{N}_2\text{H}^+)$, with evolutionary stage in three selected cores (Chen et al. 2010). Here we further investigate the possibility of using $D_{\text{frac}}$ as an evolutionary probe for high-mass protostellar/cluster cores by searching its correlation with some indicators in three more clouds of high IR extinction.

In early stages of star formation process, the low-temperature environment nurtures a peculiar chemistry with high deuterium enrichment as a result of exothermic deuteration reactions and significant depletion of CO and other neutral species. Deuterium enrichment is primarily initiated by the reaction

$$\text{H}_3^+ + \text{HD} \rightleftharpoons \text{H}_2\text{D}^+ + \text{H}_2,$$  

which is exothermic in the forward direction with $\Delta E/k = 230$ K (Millar et al. 1989). At very low temperature ($T < 20$ K), the back reaction becomes negligible, which results in an enhancement of H$_2$D$^+$ (Stark et al. 1999, 2004; Caselli et al. 2003, 2008; Vastel et al. 2006; van der Tak et al. 2005; Harju et al. 2006; Friesen et al. 2010) and even multiply deuterated H$_3^+$ (Vastel et al. 2004; Parise et al. 2010; Roberts et al. 2003). Deuteration is further enhanced in cold cores after the removal of the gas-phase CO, the major destroyer of H$_2$D$^+$, due to depletion of molecular species on dust grains (Ceccarelli et al. 2007; Bergin & Tafalla 2007; van der Tak 2006; Akaiwa 2008; Millar 2005). Indeed, deuterated species are often observed with an enhancement of 2–3 orders of magnitude in star-forming cores (Crapsi et al. 2005; Fontani et al. 2006, 2008; Vastel et al. 2006; Pillai et al. 2007) over the local interstellar value of 1.51 × 10$^{-5}$ (Oliveira et al. 2003). Chemical models anticipate some correlation between the deuterium fractionation and the CO depletion factor, $f_D$, which increases in the prestellar phase and declines...
later in the protostellar phase as the mantle sublimation occurs (Ceccarelli et al. 2007; Crapsi et al. 2005; Emprechtinger et al. 2009). This correlation has been recognized in the same molecular clouds show better correlation that indicates environmental influences, such as magnetic field strength, amount of turbulence, external radiation field, etc. (Crapsi et al. 2005; Emprechtinger et al. 2009). On the other hand, early studies of HMPOs often did not show a consistent behavior of deuterium fractionation with evolutionary stage other than a general enhancement (Fontani et al. 2006; Pillai et al. 2007). In the study of G28.34+0.06 (Chen et al. 2010), we started off our sample with cores in one IRDC and found a moderate decreasing trend in the deuterium fractionation of N$_2$H$^+$ with evolutionary stages from a massive starless core (MM9), a more evolved core with fragmentation and molecular outflows (MM4; Wang et al. 2011), to a UC H$\text{ii}$ core (MM9), a more evolved core with fragmentation and molecular outflows (Table 1) and possibly at the earliest stage. We consider them to be quiescent and perhaps prestellar cores in this study. Our sample of cores has gas temperatures from 14 to 21 K, which are within a promising range to detect variation in $f_D$ based on dust mantle sublimation (Collings et al. 2003). These cores are generally colder than those considered in previous studies (Fontani et al. 2006, 2011).

We select cores in three massive star-forming regions of similar luminosity ($L \sim 10^4 L_\odot$) to probe a sequence of evolutionary stages: one IRDC, G34.43+0.24 (hereafter G34.43; Rathborne et al. 2006), and two HMPOs, IRAS 18151$-$1208 and IRAS 18223$-$1243 (hereafter I18151 and I18223, respectively; Sridharan et al. 2002). All three regions harbor multiple cores at different evolutionary stages, and discussions of individual clouds are provided in the Appendix. To better parameterize the evolutionary stage with gas properties, we limit our sample to cores with available ammonia gas temperatures from a survey conducted by Sakai et al. (2008). This renders eight cores in G34.43, three cores in I18151, and four cores in I18223.

Table 1 lists the selected cores and their known properties such as gas temperature, $T_g$, integrated flux density at 1.2 mm, $F_{1.2 \text{mm}}$, core size, $2R$, and molecular number density, $n_{\text{H}_2}$. In addition, 4 out of the 15 selected cores are not associated with any known outflows (Table 1) and possibly at the earliest stage. We consider them to be quiescent and perhaps prestellar cores in this study. Our sample of cores has gas temperatures from 14 to 21 K, which are within a promising range to detect variation in $f_D$ based on dust mantle sublimation (Collings et al. 2003). These cores are generally colder than those considered in previous studies (Fontani et al. 2006, 2011).

Based on previous studies, e.g., Chen et al. (2010) and Fontani et al. (2011), we assess the use of $D_{\text{frac}}$ as an evolutionary probe with a large sample of cores, particularly for evolutionary stages before hot molecular cores (HMCs) and UC H$\text{ii}$ regions. In this study, a similar strategy is employed to compare $D_{\text{frac}}$ among cores in similar IRDCs to reduce the environmental fluctuations among selected cores. Moreover, we also investigate the behavior of the $N(N_2D^+)/N(N_2H^+)$ ratio

<table>
<thead>
<tr>
<th>Core</th>
<th>R.A. (J2000)</th>
<th>Decl. (J2000)</th>
<th>$T_g$ (K)</th>
<th>$F_{1.2 \text{mm}}$ (Jy)</th>
<th>$2R$ (pc)</th>
<th>log $n_{\text{H}_2}$ (cm$^{-3}$)</th>
<th>Outflow ($Y/N$)</th>
<th>Remark</th>
</tr>
</thead>
<tbody>
<tr>
<td>MM1</td>
<td>18 53 18.0</td>
<td>+01 25 24</td>
<td>18.5</td>
<td>4.01</td>
<td>0.19</td>
<td>6.44</td>
<td>Y</td>
<td>HMC</td>
</tr>
<tr>
<td>MM2</td>
<td>18 53 18.6</td>
<td>+01 24 40</td>
<td>18.8</td>
<td>4.33</td>
<td>0.12</td>
<td>5.42</td>
<td>Y</td>
<td>UC H$\text{ii}$</td>
</tr>
<tr>
<td>MM3</td>
<td>18 53 20.4</td>
<td>+01 28 23</td>
<td>15.5</td>
<td>1.02</td>
<td>0.38</td>
<td>4.95</td>
<td>Y</td>
<td></td>
</tr>
<tr>
<td>MM4</td>
<td>18 53 19.0</td>
<td>+01 24 08</td>
<td>17.6</td>
<td>0.86</td>
<td>0.38</td>
<td>4.87</td>
<td>Y</td>
<td></td>
</tr>
<tr>
<td>MM5</td>
<td>18 53 19.8</td>
<td>+01 23 30</td>
<td>14.3</td>
<td>2.24</td>
<td>0.89</td>
<td>4.65</td>
<td>Y</td>
<td></td>
</tr>
<tr>
<td>MM6</td>
<td>18 53 18.6</td>
<td>+01 27 48</td>
<td>14.0</td>
<td>0.43</td>
<td>0.62</td>
<td>4.41</td>
<td>N</td>
<td></td>
</tr>
<tr>
<td>MM8</td>
<td>18 53 16.4</td>
<td>+01 26 20</td>
<td>17.2</td>
<td>0.36</td>
<td>0.52</td>
<td>4.44</td>
<td>Y</td>
<td></td>
</tr>
<tr>
<td>MM9</td>
<td>18 53 18.4</td>
<td>+01 28 14</td>
<td>13.9</td>
<td>0.53</td>
<td>0.67</td>
<td>4.41</td>
<td>N</td>
<td></td>
</tr>
<tr>
<td>IRAS 18151$-$1208 (HMPO; $d = 3.0$ kpc)</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>MM1</td>
<td>18 17 58.0</td>
<td>−12 07 27</td>
<td>20.8</td>
<td>3.6</td>
<td>0.25</td>
<td>5.94</td>
<td>Y</td>
<td>HMPO</td>
</tr>
<tr>
<td>MM2</td>
<td>18 17 50.4</td>
<td>−12 07 55</td>
<td>17.8</td>
<td>2.6</td>
<td>0.34</td>
<td>5.62</td>
<td>Y</td>
<td>HMSC</td>
</tr>
<tr>
<td>MM3</td>
<td>18 17 52.2</td>
<td>−12 06 56</td>
<td>16.0</td>
<td>0.9</td>
<td>0.40</td>
<td>5.05</td>
<td>N</td>
<td></td>
</tr>
<tr>
<td>IRAS 18223$-$1243 (HMPO; $d = 3.7$ kpc)</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>MM1</td>
<td>18 25 10.5</td>
<td>−12 42 26</td>
<td>17.5</td>
<td>2.5</td>
<td>0.55</td>
<td>4.88</td>
<td>Y</td>
<td>HMPO</td>
</tr>
<tr>
<td>MM2</td>
<td>18 25 09.5</td>
<td>−12 44 15</td>
<td>15.1</td>
<td>0.6</td>
<td>0.47</td>
<td>4.88</td>
<td>N</td>
<td>HMSC</td>
</tr>
<tr>
<td>MM3</td>
<td>18 25 08.3</td>
<td>−12 45 28</td>
<td>16.2</td>
<td>0.8</td>
<td>0.31</td>
<td>5.42</td>
<td>Y</td>
<td>HMSC</td>
</tr>
<tr>
<td>MM4</td>
<td>18 25 07.2</td>
<td>−12 47 54</td>
<td>15.5</td>
<td>0.3</td>
<td>0.52</td>
<td>4.43</td>
<td>Y</td>
<td>HMSC</td>
</tr>
</tbody>
</table>

Notes.

$^a$ Gas temperature based on NH$_3$ observations (Sakai et al. 2008).

$^b$ Integrated 1.2 mm flux density and the deconvolved core size, defined as the geometric mean of the major and minor FWHMs (Beuther et al. 2002a; Rathborne et al. 2006).

$^c$ Compiled from literature using Spitzer 4.5 $\mu$m emission and molecular outflows (Beuther et al. 2002b; Chambers et al. 2009; López-Sepulcre et al. 2011; Marseille et al. 2008).

$^d$ Classification from previous studies (Rathborne et al. 2006, 2008; Sridharan et al. 2002, 2005).
with the CO depletion factor through C$^{18}$O observations and estimate the electron abundance. In Section 2, we describe the observations and related parameters. We then explain in Section 3 the derivation of $D_{\text{frac}}$ with self-consistent spectral fits for N$_2$H$^+$ and N$_2$D$^+$ as well as the determination of the CO depletion factor. Lastly, in Section 4, we discuss the use of the N(N$_2$H$^+)/$N(N$_2$D$^+$) ratio as an evolutionary probe as well as the upper limits for the degree of ionization and its implications.

2. OBSERVATIONS AND DATA REDUCTION

We observed N$_2$H$^+$ (3–2) at 279.511780 GHz, N$_2$D$^+$ (3–2) at 231.321864 GHz, and C$^{18}$O (2–1) at 219.56036 GHz toward selected cores in G34.43, I18151, and I18223 with the 10 m Arizona Radio Observatory Submillimeter Telescope (SMT) on Mount Graham, AZ. The observations were carried out between 2008 November and 2011 April in the beam-switching mode for N$_2$H$^+$ and N$_2$D$^+$ and in the absolute position-switching mode for C$^{18}$O to correctly subtract the background because C$^{18}$O emission is supposed to be extended. The pointing centers are given in Table 1 with typical uncertainty of $\sim 3''$. The primary beam is about 27'' for N$_2$H$^+$, 32'' for N$_2$D$^+$, and 34'' for C$^{18}$O. The spectral resolution is 1 MHz, corresponding to a velocity resolution of 1.07 and 1.30 km s$^{-1}$ for N$_2$H$^+$ and N$_2$D$^+$, respectively, and 0.25 MHz, equivalent to 0.34 km s$^{-1}$, for C$^{18}$O. The temperature scale $T_A^*$ was obtained using standard vane calibration, and the main beam temperature, $T_{mb}$, was derived through $T_A^* = T_{mb} / \eta_{mb}$ with a main beam efficiency $\eta_{mb} = 0.75$. Typical system temperature during the observations was around 200–300 K and the respective rms noise level for each observation is given in Table 1. Data reduction was performed with the CLASS package (Guilloteau & Lucas 2000; see also http://www.iram.fr/IRAMFR/GILDAS).

3. DATA ANALYSIS AND SPECTRAL FITS

Except for the N$_2$D$^+$ in G34.43–MM8 (Figure 1(g)), all three molecular lines are detected in emission toward every core. The spectra for cores in G34.43 are shown in Figure 1 while those for in I18151 and I18223 in Figures 2 and 3, respectively. We derive $D_{\text{frac}}$ by analyzing the N$_2$H$^+$ and N$_2$D$^+$ spectra with a self-consistent spectral fit. The CO depletion factor, $f_D$, is also estimated with the observed C$^{18}$O spectra and available 1.2 mm continuum flux density.

3.1. Self-consistent Spectral Fits for N$_2$H$^+$ and N$_2$D$^+$

In some cores, the emission of N$_2$D$^+$ is undesirably weak and it becomes more challenging to constrain the spectral fit parameters. Instead of performing an independent spectral fit for N$_2$D$^+$, we improve the model described in Chen et al. (2010) to perform a self-consistent fit for the N$_2$H$^+$ and N$_2$D$^+$ spectra using $D_{\text{frac}}$ as a scaling factor. Because of the numerous hyperfine components, we fit each spectrum of every core with a synthetic spectrum comprised of 38 hyperfine components with updated line frequencies and spontaneous emission rates (Pagani et al. 2009). For each individual source, all the hyperfine components of every $J$-level are assumed to be in thermal equilibrium at a single excitation temperature, $T_g$, adopted from the ammonia gas temperature in Sakai et al. (2008). The synthetic spectra are described by three more parameters: the total column density, N(N$_2$H$^+$), the systemic velocity, $v_{LSR}$, and the FWHM as line width, $\Delta v$. Model spectra are optimized with the minimization of the reduced $\chi^2$ value, $\chi^2$, and the results are listed in Table 2. Note that the uncertainties of the adopted $T_g$ (Sakai et al. 2008) are also incorporated into the uncertainties of all the derived spectral parameters.

Taking the cosmic background temperature, $T_{bg} = 2.7$ K, into account, we derive the optical depth of an observed spectrum
Table 2
Parameters of Spectral Fits for N2H+ and N2D+

<table>
<thead>
<tr>
<th>Core</th>
<th>$\sigma_{N2H^+}$ (mK)</th>
<th>$\sigma_{N2D^+}$ (mK)</th>
<th>$N(N2H^+)$ ($10^{12}$ cm$^{-2}$)</th>
<th>$v_{LSR}$ (km s$^{-1}$)</th>
<th>$\Delta v$ (km s$^{-1}$)</th>
<th>$D_{\text{max}}$</th>
<th>$\chi^2$</th>
<th>$\tau_{\text{max}}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>G34.43+0.24</td>
<td></td>
<td></td>
<td></td>
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<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>MM1</td>
<td>44</td>
<td>9.5</td>
<td>17 ± 2</td>
<td>57.550 ± 0.008</td>
<td>4.81 ± 0.06</td>
<td>(39 ± 6) $\times 10^{-4}$</td>
<td>3.7</td>
<td>0.77</td>
</tr>
<tr>
<td>MM2</td>
<td>20</td>
<td>7.7</td>
<td>13 ± 1</td>
<td>57.579 ± 0.005</td>
<td>4.54 ± 0.05</td>
<td>(80 ± 7) $\times 10^{-4}$</td>
<td>9.8</td>
<td>0.61</td>
</tr>
<tr>
<td>MM3</td>
<td>20</td>
<td>7.8</td>
<td>6.0 ± 0.6</td>
<td>59.66 ± 0.01</td>
<td>4.20 ± 0.03</td>
<td>0.007 ± 0.002</td>
<td>3.1</td>
<td>0.32</td>
</tr>
<tr>
<td>MM4</td>
<td>21</td>
<td>8.8</td>
<td>5.8 ± 0.5</td>
<td>57.56 ± 0.01</td>
<td>4.76 ± 0.03</td>
<td>0.022 ± 0.002</td>
<td>4.2</td>
<td>0.27</td>
</tr>
<tr>
<td>MM5</td>
<td>19</td>
<td>7.1</td>
<td>1.8 ± 0.3</td>
<td>57.89 ± 0.03</td>
<td>3.45 ± 0.06</td>
<td>0.033 ± 0.005</td>
<td>1.6</td>
<td>0.12</td>
</tr>
<tr>
<td>MM6</td>
<td>23</td>
<td>10.5</td>
<td>0.59 ± 0.09</td>
<td>58.27 ± 0.06</td>
<td>2.3 ± 0.1</td>
<td>0.11 ± 0.02</td>
<td>0.8</td>
<td>0.05</td>
</tr>
<tr>
<td>MM8</td>
<td>24</td>
<td>8.5</td>
<td>0.33 ± 0.04</td>
<td>57.2 ± 0.1</td>
<td>3.4 ± 0.3</td>
<td>0.000 ± 0.02</td>
<td>1.2</td>
<td>0.02</td>
</tr>
<tr>
<td>MM9</td>
<td>17</td>
<td>8.9</td>
<td>1.6 ± 0.2</td>
<td>58.89 ± 0.02</td>
<td>3.04 ± 0.06</td>
<td>0.058 ± 0.007</td>
<td>2.5</td>
<td>0.11</td>
</tr>
</tbody>
</table>

IRAS 18151−1208

| MM1  | 25                     | 10.6                   | 3.9 ± 0.4                       | 33.203 ± 0.008           | 2.94 ± 0.03              | 0.010 ± 0.002      | 6.0      | 0.27             |
| MM2  | 22                     | 7.9                    | 6.6 ± 0.8                       | 29.706 ± 0.007           | 4.01 ± 0.04              | 0.019 ± 0.001      | 3.9      | 0.36             |
| MM3  | 20                     | 8.3                    | 1.1 ± 0.3                       | 30.67 ± 0.02             | 2.40 ± 0.06              | 0.064 ± 0.007      | 2.4      | 0.10             |

IRAS 18223−1243

| MM1  | 30                     | 8.6                    | 3.5 ± 0.4                       | 45.41 ± 0.02             | 3.69 ± 0.05              | 0.021 ± 0.002      | 3.4      | 0.20             |
| MM2  | 38                     | 7.9                    | 1.9 ± 0.3                       | 45.20 ± 0.05             | 3.7 ± 0.1                | 0.033 ± 0.005      | 1.1      | 0.11             |
| MM3  | 40                     | 8.6                    | 4.2 ± 0.4                       | 45.54 ± 0.03             | 4.42 ± 0.07              | 0.021 ± 0.002      | 1.5      | 0.21             |
| MM4  | 43                     | 8.4                    | 0.9 ± 0.2                       | 45.93 ± 0.07             | 2.5 ± 0.2                | 0.015 ± 0.009      | 1.2      | 0.08             |

Figure 2. (a)–(c): Similar to Figure 1 but for I18151–MM1, MM2, and MM3. The spectra of N2H+ (3–2) are shifted by 9 K and those of N2D+ (3–2) are multiplied by 10 and shifted by 7 K.

Figure 3. (a)–(d): Similar to Figure 1 but for I18223–MM1, MM2, MM3, and MM4. The spectra of N2H+ (3–2) are shifted by 10 K and those of N2D+ (3–2) are multiplied by 10 and shifted by 8 K.

with

$$\tau(\nu) = -\ln \left[ 1 - \frac{T_{\text{mb}}(\nu)}{J(T_g) - J(T_{\text{bg}})} \right],$$

(2)

where $T_{\text{mb}}(\nu)$ is the main beam temperature of the spectra and $J(T) \equiv (h\nu/k)(e^{h\nu/kT} - 1)$. In general, the spectra have fairly small optical depths if a beam filling factor of unity is assumed. The optimized spectral model also delivers an estimate for the N2H+ optical depth by integrating optical depths of all the hyperfine components. The maximum optical depth, $\tau_{\text{max}}$, is about 0.8 in G34.43–MM1 (Table 2). Emissions of N2H+ and N2D+ in all the observed cores remain optically thin. Although sub-structures within our observing beam sizes cannot be completely ruled out, the emission in these early phases of core evolution is mostly attributed to large scales. In the example of G28.34+0.06, the integrated flux observed with the
Submillimeter Array is less than 10% of the total flux observed with the single-dish telescope SMT (Chen et al. 2010).

3.2. The CO Depletion Factor

The CO depletion factor, $f_D$, is defined as the ratio of the canonical CO abundance, $x(CO)_{can}$, to the observed CO abundance, $x(CO)_{obs}$,

$$f_D = \frac{x(CO)_{can}}{x(CO)_{obs}} = \frac{x(C^{18}O)_{can}}{x(C^{18}O)_{obs}}.$$ (3)

Using the $C^{18}$O abundance of 1.7 \times 10^{-7} in the solar neighborhood (Frerking et al. 1982) and the abundance gradients of $\Delta \log (C/H)/\Delta R = -0.066 \text{ dex kpc}^{-1}$ and $\Delta \log (O/H)/\Delta R = -0.065 \text{ dex kpc}^{-1}$ in the Galactic disk (Wilson & Matteucci 1992), the canonical abundance of $C^{18}$O is estimated to be

$$x(C^{18}O)_{can} = 1.7 \times 10^{-7} \times 10^{-0.131(D_GC-D_O)},$$ (4)

where $D_{GC}$ is the Galactocentric distance of the core and $D_O = 8.5 \text{ kpc}$ is the distance of the Sun to the Galactic center. Given the location of our IRDCs, $x(C^{18}O)_{can} = 3.80 \times 10^{-7}$, $3.92 \times 10^{-7}$, and $4.68 \times 10^{-7}$ for G34.43, I18151, and I18223, respectively.

Overall, the observed brightness temperature, $T_{mb}$, is smaller than the kinetic temperature, $T_g$, and renders fairly small optical depths. The maximum optical depth estimated with Equation (2) in individual IRDCs is 0.5 for G34.43–MM2, 0.5 for I18151–MM3, and 0.8 for I18223–MM1. Assuming that all rotational levels are thermalized, we determine the column density of $C^{18}$O with the method based on Caselli et al. (2002) that accommodates the effect of background emission at $T_{bg}$,

$$N(C^{18}O) = \frac{3h}{8\pi^3} \frac{1}{\mu^2 S_{21}} W(C^{18}O) \frac{Q(T_g)}{T_g - T_{bg}} e^{E_{up}/kT_g} (e^{h\nu/kT_g} - 1),$$ (5)

where $Q(T_g)$ is the partition function, $\mu^2 S_{21} = 0.02440 \text{ Debye}^2$ for the $J = 2 \rightarrow 1$ transition, $\nu_0$ is the transition rest frequency, $E_{up} = 15.8 \text{ K}$ is the upper level energy, and $W(C^{18}O)$ is the integrated brightness temperature in velocity (Table 1). Since some of the spectra do not resemble a Gaussian profile, direct integration in the channels with significant emission is performed to obtain $W(C^{18}O)$ without fitting a Gaussian profile, and the derived $N(C^{18}O)$ is listed in Table 3.

The observed $C^{18}$O fractional abundance, $x(C^{18}O)_{obs}$, depends on the column density of $H_2$, $N_{H_2}$, and $x(C^{18}O)_{obs} = N(C^{18}O)_{obs}/N_{H_2}$. In the attempt to reduce the uncertainty in deriving $x(C^{18}O)_{obs}$, we first match the angular resolutions between the $C^{18}$O and dust continuum observations by convolving the 1.2 mm continuum maps in the literature (beam size = 11”; Beuther et al. 2002a; Rathborne et al. 2006) with the 34” beam of our $C^{18}$O observations. The column density of $H_2$ is estimated with the 1.2 mm peak flux density, $S_{1.2\text{mm}}$, arising from warm dust

$$N_{H_2} = \frac{S_{1.2\text{mm}}}{\kappa_{1.2\text{mm}}} B_{\nu}(T_d) \Omega_b \mu m_{H_2},$$ (6)

where $\kappa_{1.2\text{mm}} = 0.005 \text{ cm}^2 \text{ g}^{-1}$ is the dust opacity assuming a gas-to-dust mass ratio of 100 (Shepherd & Watson 2002), $B_{\nu}(T_d)$ is the Planck function at dust temperature, $T_d$, $\Omega_b$ is the solid angle subtended by the convolved beam size of 34”, $\mu = 1.36$ is the mean molecular weight, and $m_{H_2}$ is the mass of $H_2$ molecule.

For warmer cores in our sample, the averaged dust temperature, $T_d$, has been found from studies of the spectral energy distributions (SEDs; Table 3; Rathborne et al. 2005; Marseille et al. 2008; Beuther et al. 2010). However, most cores in our sample remain as extinction features in the near- or mid-IR, and it is challenging to derive their dust temperatures. Sensitive mid- and far-IR observations, such as Herschel, will offer better opportunities to constrain dust emission properties, including temperature, in cold clumps of IRDCs (e.g., Beuther et al. 2010;
Stutz et al. 2010). Alternatively, we adopt the gas temperature, $T_g$, for the conversion between $S_{1.2\text{mm}}$ to $N_{\text{H}_2}$ when dust temperature is unavailable. In case the thermal coupling between dust and gas is not ideal, this assumption may underestimate $T_g$ and hence overestimate $N(\text{H}_2)$ by a factor of $<2$ in our sample. In the case of G34.43–MM2, no SED study is found to constrain its dust temperature. Since the core is associated with a UC H II region, we expect its averaged dust temperature to be warmer with respect to MM1 and sets a lower limit of $T_g \gtrsim 34$ K for MM2.

Once the observed $^{18}$O abundance, $x(\text{C}^{18}\text{O})_{\text{obs}}$, is determined, the CO depletion factor, $f_D$, can be computed with Equation (3) accordingly, and the results are summarized in Table 3.

4. RESULTS AND DISCUSSION

Except for G34.43–MM8 with an undetected $N_2D^+$ emission, all of our cores show a general enhancement of 2–3 orders of magnitudes in $D_{\text{frac}}$ (Table 2) over the local interstellar value of $1.51 \times 10^{-5}$ (Oliveira et al. 2003). Note that the $D_{\text{frac}}$ in G34.43 spans a fairly large range from 0.0039 to 0.11, nearly a factor of 30. The deuterium fractionation, $D_{\text{frac}}$, is compared with the gas temperature, $T_g$, the fitted line width, $\Delta v$, and the CO depletion factor, $f_D$, in Figure 4. A clear decreasing trend in $D_{\text{frac}}$ with both $T_g$ and $\Delta v$ but a weaker increasing trend with $f_D$ can be seen. Although these behaviors generally agree with expectations based on chemical models, an analytical formula to describe the dependence is not obvious with the large scatters in Figure 4. To search for dependence, we perform statistical tests between $D_{\text{frac}}$ and other parameters to evaluate the correlation along with the significance, which gives the likelihood for the correlation occurring by chance. The decreasing trend between $D_{\text{frac}}$ and $T_g$ (Figure 4(a)) has a Spearman’s $\rho$ rank correlation coefficient of $\rho = -0.67$ with a significance of 0.6% and Kendall’s $\tau$ rank correlation coefficient of $\tau = -0.50$ with a significance of 1.0%. While the correlation between $D_{\text{frac}}$ and $\Delta v$ (Figure 4(b)) gives $\rho = -0.61$ with a significance of 1.6% and $\tau = -0.49$ with a significance of 1.2%. On the other hand, the dependence between $D_{\text{frac}}$ and $f_D$ shows larger scatters (Figure 4(c)). When excluding G34.43–MM1 with an unusually large $f_D$, we find an improved correlation that has $\rho = 0.49$ with a significance of 7.8% and $\tau = 0.34$ with a significance of 9.0%.

4.1. Deuterium Fractionation as an Evolutionary Probe

Overall, a monotonically decreasing trend in $D_{\text{frac}}$ with both increasing gas temperature, $T_g$, and fitted line width, $\Delta v$, is discerned (Figures 4(a) and (b)). While examining cores in individual clouds, there seems to be a slightly better correlation, implying a possible cloud-to-cloud variation due to the influence of environments as previously suggested in the studies of low-mass cores (Crapsi et al. 2005; Emprechtinger et al. 2009). Miettinen et al. (2011) also suggest relatively large environmental variations in the cosmic-ray ionization rates in massive IRDC cores. In particular, quiescent cores with no outflow activities, i.e., G34.43–MM6, G34.43–MM9, I18151–MM3, and I18223–MM2, all have the lowest temperature (Table 1) and the largest $D_{\text{frac}}$ (Table 2) as well. Since warm and turbulent gas is more likely to be associated with evolved cores, the observed $D_{\text{frac}}$ suggests a decreasing dependence with evolutionary stage. For a better determination of their evolutionary stage, one may desire to compare with theoretical evolutionary models, which depend on several physical parameters, such as bolometric temperature, bolometric luminosity, and envelope mass (Froebrich 2005). However, most of our selected cores, especially those with the largest $D_{\text{frac}}$, do not have observations in the mid- and far-IR wavebands to better constrain their dust temperature and bolometric luminosity. Alternatively, we compare $D_{\text{frac}}$ with gas temperature and line width instead of bolometric temperature and luminosity.

A few previous studies have reported an anti-correlation between deuterium fractionation and evolutionary stage of massive protostellar cores. Chen et al. (2010) found $D_{\text{frac}} = 0.017–0.052$ in three cores at different evolutionary stages within the IRDC G28.34+0.06, including a massive starless...
core (MM9), a core with fragmentation and outflow activities (MM4; Wang et al. 2011), and a UC H II region (MM1), and suggested a decreasing trend in $D_{\text{frac}}$ with evolutionary stage. A subsequent study by Fontani et al. (2011) significantly improved the statistics with a sample of 27 cores and also revealed this decreasing trend with values of $D_{\text{frac}}$ in the range of 0.012–0.7, 0.017–0.4, and 0.017–0.08 for their observed HMSCs, HMPOs, and UC H II regions, respectively. In particular, they found an anti-correlation between $D_{\text{frac}}$ and $T_g$. Miettinen et al. (2011) further reported a decreasing trend in $D_{\text{frac}}$ in the ratio of $N(DCO^+)/N(HCO^+)$ = 0.0002–0.014 with gas temperature in their sample of seven IRDC cores. They also reported $D_{\text{frac}} = 0.002–0.028$ for the four cores with higher gas temperature. Our values of $D_{\text{frac}}$ are in the range of 0.0039–0.11, which are comparable to the values obtained by Fontani et al. (2011) and Miettinen et al. (2011). The anti-correlation between $D_{\text{frac}}$ and $T_g$ is also seen in our results (Figure 4(a)).

Given the gas temperature range of $T_g = 14–21$ K, the corresponding thermal line width of N2H$^+$ is merely $\Delta v_{\text{th}} = 0.15–0.18$ km s$^{-1}$. The observed line width in the range of 2.3–4.8 km s$^{-1}$ is dominated by nonthermal motions, possibly arising from turbulent motions among clumps. In Figure 5, we compare the line width of our N2H$^+$ (3–2) spectra with line widths of N2H$^+$ (1–0) and NH3 (1, 1), (2, 2), and (3, 3) spectra observed by Sakai et al. (2008). The N2H$^+$ (1–0) observations had a smaller beam of 18′′ while the NH3 observations had a much larger beam of 73′′ with respect to our 27′′ beam for N2H$^+$ (3–2). Between the two transitions of N2H$^+$, the J = 3–2 transition with higher $E_{\text{up}} = 26.8$ K shows a broader line width than the J = 1–0 with lower $E_{\text{up}} = 4.5$ K, as warmer gas is expected to be more turbulent (Figure 5(a)). In general, NH3 lines have a much lower critical density of $n_{\text{crit}} = 2 \times 10^5$ cm$^{-3}$ (Evans 1999) and tend to trace the outer part of the cores with respect to N2H$^+$ lines with $n_{\text{crit}} = 10^5$ cm$^{-3}$. Except in the two quiescent cores, G34.43–MM6 and I18151–MM3, line widths of the NH3 (1, 1) and (2, 2) spectra are comparable to those of N2H$^+$ (1–0) but smaller than those of N2H$^+$ (3–2) (Figures 5(b) and (c)). The two quiescent cores are probably in a very early stage where turbulence dissipation may occur to produce smaller line width in the inner part of higher density (Goodman et al. 1998). In a number of more evolved cores, the NH3 (3, 3) emissions with much higher $E_{\text{up}} = 124.5$ K are detected and show much larger line width, even up to 7.2 km s$^{-1}$ in the case of G34.43–MM3 (Figure 5(d)). Since all these evolved cores are associated with outflow activities, the NH3 (3, 3) emission is tracing the hot gas which could be in the outflows (Zhang et al. 2002).

Unlike NH3 and NH2D, which are affected by grain surface reactions (Güttler et al. 2002; Bottinelli et al. 2010), N2D$^+$ and N2H$^+$ are pure gas-phase reactants and do not participate condensation and subsequent sublimation of ice mantles. Compared to other molecular species, the deuterium fractionation of N2H$^+$ better reflects the physical conditions at the present time without being confused by evaporation of mantles which had formed at earlier times with enhanced deuteration (Emprechtinger et al. 2009). In a sample of Taurus cores, a clear increasing trend in the deuteron fractionations of both NH3 and N2H$^+$ was observed in prestellar cores (Crapsi et al. 2005; Hatchell 2003), whereas in protostellar cores, $D_{\text{frac}}$ shows a faster decreasing trend with dust temperature than does the $N(NH_2D)/N(NH_3)$ ratio (Emprechtinger et al. 2009). For high-mass protostellar cores within a similar gas temperature range, we note that the correlation between $D_{\text{frac}}$ and $T_g$ appears stronger in our cores than does the $N(NH_2D)/N(NH_3)$ ratio (Pillai et al. 2007).

### 4.2. Deuterium Fractionation and the CO Depletion Factor

To further examine the relationship between deuterium fractionation and the CO depletion, we computed the C18O column density and the CO depletion factor, $f_{\text{depl}}$, as described in Section 3.2. The results are listed in Table 3 and shown in Figure 4(c). When excluding G34.43–MM1, which has the
largest value of $f_D$, we find an increasing trend in $D_{\text{frac}}$ with $f_D$. This agrees with the general expectations from chemical models that CO is the major destroyer of $\text{H}_2^+$, $\text{H}_2\text{D}^+$, $\text{N}_2\text{H}^+$, and $\text{N}_2\text{D}^+$ (Caselli et al. 1998). As the envelope heats up, the CO abundance is expected to quickly rise based on the dramatical drop of the CO sublimation timescale from $10^8$ yr at $T_d \approx 12$ K to 0.1 yr at $T_d \approx 20$ K (Collings et al. 2003). The warmer temperature together with the return of gas-phase CO can alter the competition in the chemical networks and brings a drop in $D_{\text{frac}}$ (Roueff et al. 2005; Aikawa et al. 2005; Aikawa 2008). When CO returns to the gas phase, it will quickly react with $\text{N}_2\text{H}^+$ and $\text{N}_2\text{D}^+$ to form HCO$^+$ and DCO$^+$, respectively (Lee et al. 2004). However, one should be cautious about possible chemical stratification once the CO sublimation starts in the central warm region. As a core warms up, the $\text{N}_2\text{H}^+$ and $\text{N}_2\text{D}^+$ emissions tend to trace the cold outer region whereas the CO emission is dominated in the central region. In the study of the Ophiuchus B2 core, Friesen et al. (2010) found that $D_{\text{frac}}$ increases at greater projected distances from the embedded sources. When the observed emission arises from a partially filled volume, the beam-averaged abundance for each species will start to deviate from the actual abundance used in chemical models. Observations with high angular resolutions will help to image the spatial distributions and reduce the confusion in comparing abundances.

In the case of G34.43–MM1, an unusually large value of $N_{\text{H}}$, and hence $f_D$ is obtained. Millimeter interferometric studies (Cortes et al. 2008; Rathborne et al. 2008) reveal a very strong ($L_{\text{bol}} \approx 2 \times 10^4 L_\odot$) and compact ($2 R \approx 0.03$ pc) source that exhibits signatures of an HMC, which is thought to have a typical temperature closer to 100 K. This source has developed a steep temperature gradient, from 34 to 100 K across core scales from 0.1 to 0.015 pc (Rathborne et al. 2008), translating to a single power-law dependence of $r^{-0.57}$. This steep temperature gradient suggests the presence of an inner region where optical depth is large to the IR photons that the photon diffusion should be considered (Kenyon et al. 1993; Osorio et al. 1999; Chen et al. 2006). In our approach to estimate $f_D$, the dust emission is likely dominated by the hot inner region while the CO emission arises from a cold and large envelope. The dust temperature, $T_d$, derived from the SED fit depends on the flux densities in the mid-IR wavebands that may suffer from significant optical depth and does not reflect the physical conditions of the hot central region where the peak of the optically thin 1.2 mm emission is produced. Such a steep temperature gradient may cause an underestimate in $T_d$ and overestimates in $N_{\text{H}}$, and $f_D$ in our current calculation. To avoid potentially misleading interpretation, we exclude the result of G34.43–MM1 when discussing the electron abundance in the following section.

4.3. The Ionization Degree

The enrichment of primary deuterated ions, e.g., $\text{H}_2\text{D}^+$, $\text{CH}_2\text{D}^+$, and $\text{C}_2\text{HD}^+$, will give rise to the enrichment of subsequent deuterated species, such as $\text{N}_2\text{D}^+$, but with lower $\text{[D]}/[\text{H}]$ abundance ratios due to the statistical nature of the fractionation process. In simple steady-state models based on gas-phase ion–molecular chemistry, an upper limit to the electron abundance, $x_e$, can be found assuming that all the deuteron enrichment originates in $\text{H}_2\text{D}^+$ and that the recombination on negatively charged grains is negligible (Wootten et al. 1979; Caselli et al. 1998; Caselli 2002). Following the method described in Caselli (2002), the deuteron fractionation, $D_{\text{frac}}$, may be expressed as a function of $x_e$ and abundances of HD, x(HD), and important neutral species, $x(m)$,

$$D_{\text{frac}} = \frac{1}{3} \frac{k_{\text{HD}} x(\text{HD})}{k_e x_e + \sum_m k_m x(m)},$$

(7)

where $k_{\text{HD}} = 1.5 \times 10^{-9} \, \text{cm}^3 \, \text{s}^{-1}$ is the rate coefficient for the reaction in Equation (1), $k_e = 6 \times 10^{-8} \, (T/300)^{-0.65} \, \text{cm}^3 \, \text{s}^{-1}$ is the dissociated recombination rate of $\text{H}_2\text{D}^+$ (Caselli et al. 1998), and $k_m$ is the destruction rate for $\text{H}_2\text{D}^+$ due to reactions with neutral species $m$, such as CO and O. The numerical factor of 1/3 accounts for the statistical branching ratio of 1/3 to transfer the deuteron in the reaction of $\text{H}_2\text{D}^+$ with $\text{N}_2$. The HD abundance is taken from the interstellar value of $x(\text{HD}) = 2\text{[D]}/[\text{H}] = 3 \times 10^{-5}$ (Oliveira et al. 2003; Caselli et al. 1998). The electron abundance $x_e$ is then given by

$$x_e = \frac{k_{\text{HD}} x(\text{HD})}{3 k_e} \frac{1}{D_{\text{frac}}} - \frac{1}{k_e} \sum_m k_m x(m).$$

(8)

Since CO is the dominant neutral species that destroys $\text{H}_2\text{D}^+$, we make an approximation by neglecting other ion–neutral reactions to get

$$\sum_m k_m x(m) \gtrsim k_{\text{CO}} x(\text{CO}) = k_{\text{CO}} \left( \frac{x(\text{CO})_{\text{can}}}{f_D} \right),$$

(9)

where $k_{\text{CO}} = 6 \times 10^{-10} \, (T/300)^{-0.5} \, \text{cm}^3 \, \text{s}^{-1}$ is the $\text{H}_2\text{D}^+$ destruction rate due to reactions with CO (Caselli et al. 1998), and $x(\text{CO})_{\text{can}} = 1.5 \times 10^{-4}$ is the canonical CO abundance at the locations of our cores. We may set an upper limit for $x_e$ to be

$$x_e \lesssim \frac{k_{\text{HD}} x(\text{HD})}{3 k_e} \frac{1}{D_{\text{frac}}} - \frac{k_{\text{CO}} x(\text{CO})_{\text{can}}}{k_e} \frac{1}{f_D},$$

$$= 3.8 \times 10^{-8} - 9.7 \times 10^{-7} \frac{f_{\text{frac}}}{f_D} \quad \text{(for } T_d = 16 \text{ K).}$$

(10)

For easy comprehension of the dependence on $D_{\text{frac}}$ and $f_D$, the numerical values are provided for the case of $T_d = 16$ K. With the derived $D_{\text{frac}}$ and $f_D$, we obtain the ionization degree in the range of $x_e = 2 \times 10^{-6}$ to $5 \times 10^{-6}$ for our selected cores (Table 3). These values lie at the high end of the ionization degrees reported in early studies of low-mass dense cores (Caselli et al. 1998; Williams et al. 1998) and massive cores (Bergin et al. 1999). Recently, Miettinen et al. (2011) derived the first estimates for ionization degrees in IRDC cores with upper limits of $x_e = 2 \times 10^{-6}$ to $2.9 \times 10^{-4}$ and lower limits of $x_e = 3 \times 10^{-9}$ to $5.6 \times 10^{-8}$. Our estimates give smaller values compared to their upper limits but are within the range bracketed by their upper and lower limits. The smaller $x_e$ upper limits are mainly attributed to the larger deuteron fractionation derived from $\text{N}_2\text{H}^+$ instead of HCO$^+$. Furthermore, our $x_e$ values show a moderate correlation with the evolutionary stage. Since more evolved cores show smaller values of $D_{\text{frac}}$ and $f_D$, the plausible correlation between $x_e$ and the evolutionary stage may lead to the decreasing trend of $D_{\text{frac}}$. Most of the cores in our sample have shown outflow signatures and likely have begun to form clusters with lower–intermediate-mass protostars. This increasing degree of ionization could be arising from accretion shocks and/or heating of the gas related to the central
protocols/cluster objects (Stahler et al. 1980; Hosokawa et al. 2010; Calvet et al. 2004). Given the porous nature of the surrounding medium (Indebetouw et al. 2006), it is possible for part of the energetic photons to reach the outer part of the core and increase the overall electron abundance (Kim & Koo 2001).

The four quiescent cores, G34.43–MM6, G34.43–MM9, I18151–MM3, I18223–MM2, also have the lowest ionization degrees, \( x_e = 2 \times 10^{-7} \) to \( 9 \times 10^{-7} \), among cores in the same IRDC. In these cores, the degree of ionization may play a role in regulating star formation efficiency through ambipolar diffusion, in which magnetic fields drift relative to a background of neutrals (Mestel & Spitzer 1956; Shu et al. 1987). In a partially ionized medium, charged particles are coupled to magnetic fields while neutrals are supported against their self-gravity through the frictional drag that they experience when drifting through ions. In addition to ambipolar diffusion, evolution of massive star-forming cores can be affected by various effects such as turbulence (McKee & Tan 2003), rotation, and magnetic fields. For a more complete picture, one needs to consider all the important supports against gravity (Myers & Goodman 1988; McKee & Ostriker 2007).

We observe emissions of \({\text{N}_2}\text{H}^+\) (3–2), \({\text{N}_2}\text{D}^+\) (3–2), and \({\text{C}}^{18}\text{O}\) (2–1) toward 15 cores in the IRDC G34.43, and the HMO I18151 and I18223. The main findings are summarized as follows.

1. A clear decreasing trend in the deuterium fractionation of \({\text{N}_2}\text{H}^+\), \( D_{\text{frac}} \), with evolutionary stage traced by increasing gas temperature and line width. This decreasing trend agrees with the findings in previous studies by Chen et al. (2010), Fontani et al. (2011), and Miettinen et al. (2011). An increasing trend, though with larger scatters, in \( D_{\text{frac}} \) with the CO depletion factor, \( f_D \), is also found. Such trend resembles the behavior of \( D_{\text{frac}} \) in the low-mass protostellar cores and suggests the use of the \((\text{N}(\text{N}_2\text{D}^+)/\text{N}(\text{N}_2\text{H}^+))\) ratio as an evolutionary probe to high-mass protostellar/cluster candidates.

2. A significant enhancement of 2–3 orders of magnitude in the \((\text{N}(\text{N}_2\text{D}^+)/\text{N}(\text{N}_2\text{H}^+))\) ratio in all detected sources over the local interstellar [\(\text{D}\)]/[\(\text{H}\)] ratio. Such enhancement agrees well with those observed in other massive star-forming cores.

3. The upper limits of electron abundance are estimated to be in the range from \( 2 \times 10^{-7} \) to \( 5 \times 10^{-6} \), which lie at the high end of the typical values observed in early studies but within the range found by Miettinen et al. (2011) in their IRDC cores. More evolved cores seem to show higher degree of ionization, which may be related to star-forming activities.

4. In the four quiescent cores, the inferred characteristic scale for ambipolar diffusion is roughly \( 10^{-3} \) pc, and the coupling parameter of \( W \lesssim 120 \) is within the regime of marginal field-neutral coupling. The physical conditions may favor turbulent cooling flows.

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APPENDIX

DISCUSSIONS ON INDIVIDUAL CLOUDS

G34.43+0.24. The IRDC G34.43 (\( d = 3.7 \) kpc) contains nine cores (Rathborne et al. 2006) with G34.43–MM2 being the most evolved core associated with the UC H\( \alpha \) region IRAS 18507+0121 of spectral type B0.5 (Molinari et al.
et al. (2008) suggested an evolutionary sequence among three
By analyzing molecular line emissions and the SEDs, Marseille
an HMC and has started internal heating with embedded
Chambers et al. 2009). Molecular outflows have also been ob-
served in G34.43–MM1, MM2, MM3, and MM4 (Sanhueza et al. 2010).
IRAS 18151–1208. The HMPO I18151 (d = 3.0 kpc) hosts four dusty cores (Beuther et al. 2002a) with MM1 being the most evolved and dominant K-band source, possibly driving H2 jets and CO outflows (Beuther et al. 2002b; Davis et al. 2004). By analyzing molecular line emissions and the SEDs, Marseille et al. (2008) suggested an evolutionary sequence among three most compact cores: from the youngest I18151–MM3 perhaps in a prestellar phase, followed by MM2 as an HMSC with an embedded, mid-IR-quiet young protostar, to the most evolved MM1 with mid-IR-bright protostars. Molecular outflows in I18151–MM1 and MM2 also suggest their more evolved stages (Marseille et al. 2008; Beuther & Sridharan 2007).
IRAS 18223–1243. The HMPO I18223 (d = 3.7 kpc) harbors a few dusty cores in a filamentary structure with 18223–MM1 most evolved as an HMPO and others as HMSCs (Sridharan et al. 2005). Large SiO line widths suggest outflow activities in 18223–MM3 and MM4 (Beuther & Sridharan 2007).

REFERENCES

van der Tak, F. S. F. 2006, Phil. Trans. R. Soc. A, 364, 3101
Wilson, T. L., & Matteucci, F. 1992, A&ARv, 4, 1