THE DISTRIBUTION OF ORTHO–H$_2$D$^+$($1_{1,0}^{-1,1,1}$) IN L1544: TRACING THE DEUTERATION FACTORY IN PRESTELLAR CORES

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ABSTRACT

Prestellar cores are unique laboratories for studying the chemical and physical conditions preceding star formation. We observed the prestellar core L1544 in the fundamental transition of ortho-H$_2$D$^+$($1_{1,0}^{-1,1,1}$) at different positions over 100$^0$. We found a strong correlation between its abundance and the CO depletion factor. We also present a tentative detection of the fundamental transition of para-D$_2$H$^+$($1_{1,0}^{-1,0,1}$) at the dust emission peak. Maps in N$_2$H$^+$, N$_2$D$^+$, HCO$^+$, and DCO$^+$ are used and interpreted with the aid of a spherically symmetric chemical model that predicts the column densities and abundances of these species as a function of radius. The correlation between the observed deuterium fractionation of H$_3^+$, N$_2$H$^+$, and HCO$^+$ and the observed integrated CO depletion factor across the core can be reproduced by this chemical model. In addition, a simpler model is used to study the H$_2$D$^+$ ortho-to-para ratio. We conclude that, in order to reproduce the observed ortho-H$_2$D$^+$ observations, the grain radius should be larger than 0.3 $\mu$m.

Subject headings: ISM: individual (L1544) — ISM: molecules — radio lines: ISM

1. INTRODUCTION

Deuterium-bearing species are good probes of the cold phases of molecular clouds prior to star formation. Many recent observations point to the fact that their abundances relative to their fully hydrogenated forms are larger, by factors up to $10^5$, than the solar neighborhood value of $\sim 1.5 \times 10^{-5}$ found by Linsky (2003). The deuterium fractionation has been evaluated in prestellar cores and low-mass protostars from observations of HCO$^+$ and N$_2$H$^+$ (Butner et al. 1995; Williams et al. 1998; Caselli et al. 2002b; Crapsi et al. 2004, 2005), H$_2$CO (Loinard et al. 2001; Bacmann et al. 2003), H$_2$S (Vastel et al. 2003), CH$_3$OH (Parise et al. 2004), and NH$_3$ (Roueff et al. 2000; Tine`e et al. 2000). The chemical fractionation process in the gas phase mainly arises from the difference between the zero-point energies of H$_2$ and HD. Almost incredibly, this can lead to a detectable quantity of triply deuterated molecules such as ND$_3$ (Linsky et al. 2002; van der Tak et al. 2002), and CD$_3$OH (Parise et al. 2004). The latter is thought to be formed mainly on dust grain surfaces (Charnley 1997) in regions where the gas-phase [D]/[H] ratio is enhanced to values larger than $\sim 0.1$ (Caselli et al. 2002a), as in the cold cores (see below). In molecular clouds, hydrogen and deuterium are predominantly in the form of H$_2$ and HD, respectively. So the HD/H$_2$ ratio should closely equal the D/H ratio. Since the zero-point energies of HD and H$_2$ differ by $\sim 410$ K, the chemical fractionation will favor the production of HD compared to H$_2$. In the dense, cold regions of the interstellar medium ($T \sim 10$ K), nearly all D will be initially absorbed into HD. The abundant ion available for interaction is H$_3^+$, which gives H$_2$D$^+$:

\begin{equation}
H_3^+ + HD \leftrightarrow H_2D^+ + H_2 + 230 \text{ K}. \tag{1}
\end{equation}

The reverse reaction does not occur efficiently in the cold dense clouds, where low-mass stars form and where the kinetic temperature is always below 25 K, the “critical” temperature above which reaction (1) starts to proceed from right to left and limits the deuteration. Therefore, the degree of fractionation of H$_2$D$^+$ becomes negligible. This primary fractionation can then give rise to other fractionations and form D$_2$H$^+$ and D$_3^+$, as first suggested by Phillips & Vastel (2003),

\begin{equation}
H_2D^+ + HD \leftrightarrow D_2H^+ + H_2 + 180 \text{ K}, \tag{2}
\end{equation}

\begin{equation}
D_2H^+ + HD \leftrightarrow D_3^+ + H_2 + 230 \text{ K}. \tag{3}
\end{equation}
We present in Figure 1 the main reactions involving these molecules. Note that the effect of the recombination of $\text{H}_3^+$ with electrons in the gas is negligible because of the low electron density in such regions. However, the effect of recombination with electrons on negatively charged grain surfaces becomes important when depletion increases (cf. Walmsley et al. 2004). The dissociation of the deuterated forms of $\text{H}_3^+$ is then responsible for the enhancement in the [D]/[H] ratio. One specific parameter can enhance this process, the depletion of neutral species (in particular, the abundant CO) from the gas phase (cf. Dalgarno & Lepp 1984). In fact, the removal of species that would normally destroy $\text{H}_3^+$ (e.g., CO; Roberts & Millar 2000) means that $\text{H}_3^+$ is more likely to react with HD and produce $\text{H}_2\text{D}^+$, $\text{D}_2\text{H}^+$, and $\text{D}_3^+$. The first model including $\text{D}_2\text{H}^+$ and $\text{D}_3^+$ (Roberts et al. 2003) predicted that these molecules should be as abundant as $\text{H}_2\text{D}^+$ (see also Flower et al. 2004).

Gas-phase species are expected to be depleted at the center of cold, dark clouds, since they tend to stick onto the dust grains. A series of recent observations has shown that, in some cases, the abundance of molecules such as CO decreases toward the core center of cold ($\leq 10 \, \text{K}$), dense ($\geq 10^4 \, \text{cm}^{-3}$) clouds. (L1498: Willacy et al. 1998; Tafalla et al. 2002, 2004; IC 5146: Kramer et al. 1999; Bergin et al. 2001; L777: Alves et al. 1999; L1544: Caselli et al. 1999; Tafalla et al. 2002; L1689B: Jessop & Ward-Thompson 2001; Bachmann et al. 2002; Redman et al. 2002; B68: Bergin et al. 2002; L1517B: Tafalla et al. 2002, 2004; L1512: Lee et al. 2003; Oph D: Bachmann et al. 2003; Crapsi et al. 2005; L1521F: Crapsi et al. 2004; L183 [L134N]: Pagani et al. 2005). These decreases in abundance have been interpreted as resulting from the depletion of molecules onto dust grains (see, e.g., Bergin & Langer 1997; Charnley 1997). It is now clear that these drops in abundance are typical of the majority of dense cores (see Tafalla & Santiago [2004] for the case of L1521E, the first starless core to be found with no molecular depletion).

In one of the most heavily CO-depleted prestellar cores, L1544, Caselli et al. (2003) detected a strong (brightness temperature $\sim 1 \, \text{K}$) ortho-$\text{H}_2\text{D}^+ (1_{10}-1_{11})$ line and concluded that $\text{H}_2\text{D}^+$ is one of the main molecular ions in the central region of this core. Encouraged by laboratory measurements (Hirao & Amano 2003), Vastel et al. (2004) detected the para-$\text{D}_2\text{H}^+$ molecule in its ground transition at 692 GHz. They found that, in the prestellar core 16293E, $\text{D}_2\text{H}^+$ is as abundant as $\text{H}_2\text{D}^+$. These studies supported chemical modeling and the inclusion of multiply deuterated species (Roberts et al. 2003, 2004; Walmsley et al. 2004; Flower et al. 2005; Aikawa et al. 2005). It appears that in dark clouds affected by molecular depletion, the deuterated forms of the molecular ion $\text{H}_3^+$ are unique tracers of the core nucleus, the future stellar cradle. Thus, their study becomes fundamental to the unveiling of the initial conditions of the process of star formation (kinematics and physical and chemical structure of prestellar cores).

In this paper, we present new observations of the $\text{H}_2\text{D}^+ (11_{10}-11_{11})$ line toward L1544, mapped over $\sim 100''$ of the dust peak emission, as well as a tentative detection of the $\text{D}_2\text{H}^+ (1_{10}-1_{11})$ line. Caselli et al. (2003) roughly estimated the size of the $\text{H}_2\text{D}^+$-emitting region in this prestellar core and suggested a radius of about 3000 AU. But this was based on a five-point map and cannot put stringent constraints on the chemical structure. In addition, a parallel study has been done by van der Tak et al. (2005), giving the analysis of the line shape profile. Here the $\text{H}_2\text{D}^+$ map is also compared with other high-density tracer maps. Due to the poor atmospheric transmission at the frequency of the para-$\text{D}_2\text{H}^+$ fundamental line, this study is limited to the ortho-$\text{H}_2\text{D}^+$ fundamental line. We present in § 5 the perspectives on this work that will be opened up by future observatories.

2. OBSERVATIONS

The observations were carried out at the Caltech Submillimeter Observatory (CSO), between 2003 November and 2005 February, under good weather conditions (225 GHz zenith opacity always less than 0.06), where the atmospheric transmission is about 30% at 372 GHz and less than 20% at 692 GHz. Scans were taken toward the peak of the 1.3 mm continuum dust emission of L1544 ($\alpha = 05^h04^m17^s21, \delta = +25^\circ42'78''$ [J2000.0]) using the chopping secondary with a throw of 3'. The 345 GHz (650 GHz) sidecab receiver with a 50 MHz acousto-optical spectrometer back end was used for all observations with a velocity resolution of 0.06 km s$^{-1}$ (0.03 km s$^{-1}$), i.e., $\sim 1.6$ channels. At the observed frequencies of 372.41385(10) GHz for the $\text{H}_2\text{D}^+ (11_{10}-1_{11})$ and 691.660483(20) for the $\text{D}_2\text{H}^+ (1_{10}-1_{11})$ lines (Amano & Hirao 2005), the CSO 10.4 m antenna has a half-power beamwidth (HPBW) of about 20'' and 11'', respectively. We mapped the area in $\text{H}_2\text{D}^+$ around the dust peak position with a grid spacing of 20'' and used the value at the peak from Caselli et al. (2003) and integrated longer. The beam efficiency at 372 GHz (692 GHz) was measured on Venus, Saturn, and Jupiter and found to be $\sim 60\%$ ($\sim 40\%$). Pointing was monitored every 1.5 hr and found to be better than 3''. In the case of $\text{H}_2\text{D}^+$, the emission is extended compared to the beam size of CSO; the efficiency is then about 70%. If the emission in $\text{D}_2\text{H}^+$ is extended compared to the beam size of 11'', then the efficiency at 692 GHz is about 60%. The data reduction was performed using the CLASS program of the GAG software developed at IRAM and the Observatoire de Grenoble.

Figure 2 shows the $\text{H}_2\text{D}^+$ and $\text{D}_2\text{H}^+$ spectra observed toward the dust peak position. A Gaussian fit to the $\text{H}_2\text{D}^+$ line gives a LSR velocity of $\sim 7.3$ km s$^{-1}$, but two peaks are clearly visible, with velocities 7.1 and 7.4 km s$^{-1}$ (van der Tak et al. 2005), as also seen in other tracers (Tafalla et al. 1998; Caselli et al. 2002b). This central position was originally observed by Caselli et al. (2003) and studied in detail by van der Tak et al. (2005); here we improved the sensitivity and used the new value of the ortho-$\text{H}_2\text{D}^+ (11_{10}-1_{11})$ line frequency, recently measured by Amano & Hirao (2005). The on-source integration time for $\text{D}_2\text{H}^+$ is about 230 minutes. The $\text{D}_2\text{H}^+$ feature can be fitted with a Gaussian with $\sigma = 0.30 \pm 0.07 \, \text{K}$, $\Delta v = 0.08 \pm 0.04 \, \text{km s}^{-1}$, and $V_{\text{LSR}} = 7.29 \pm 0.03 \, \text{km s}^{-1}$. The solid vertical line corresponds to the velocity from this Gaussian fit. It is consistent with the central
velocity of the H$_2$D$^+$ line of 7.28 ± 0.06 km s$^{-1}$. However, it is difficult to believe that the observed line width represents the real line width of the transition, as the expected thermal line width is about 0.25 km s$^{-1}$ for a kinetic temperature of 7 K, as predicted by dust temperature measurement (Evans et al. 2001; Zucconi et al. 2001). This is about 3 times larger than the observed line width. Formaldehyde observations of Bacmann et al. (2002) suggest larger gas temperatures (up to 9 K), but H$_2$CO is likely frozen in the core center, so that the measured temperature probably reflects the warmer core envelope (Young et al. 2004). At high densities (higher than $\sim 3 \times 10^4$ cm$^{-3}$), Young et al. (2004) find the gas and dust temperature to be between $\sim 7$ and 9 K, consistent with what was found by Tafalla et al. (2002) using ammonia. Below we use a temperature of 8 K for this cloud. The signal-to-noise ratio of our D$_2$H$^+$ observations is not sufficient to get constraints on the kinematics of the source, and the fitted line width probably does not represent the real line width. In absence of a possible explanation for the narrow line width for the D$_2$H$^+$ profile, we consider in the following that we only have a tentative detection and then use an upper limit.

Figure 2 shows the H$_2$D$^+$ spectra around the central position (0$^\prime$, 0$^\prime$) position for L1544. The temperatures are $T_g$ in kelvin. The vertical solid line corresponds to the velocity center of the D$_2$H$^+$ Gaussian fit (7.29 km s$^{-1}$).

![Fig. 2.—Ortho-H$_2$D$^+$ and para-D$_2$H$^+$ observations at the dust peak emission corresponding to the (0$^\prime$, 0$^\prime$) position for L1544. The temperatures are $T_g$ in kelvin. The vertical solid line corresponds to the velocity center of the D$_2$H$^+$ Gaussian fit (7.29 km s$^{-1}$).](image)

foreground layer redshifted ($\sim 0.08$ km s$^{-1}$) relative to the high-density core, as found by (Williams et al. 1999) in the case of N$_2$H$^+$(1–0) mapped at high spatial resolution. A more detailed study of the H$_2$D$^+$ line profile toward the L1544 dust peak has been recently carried out by van der Tak et al. (2005), who suggested that the observed H$_2$D$^+$ line, besides being broadened by the central infall, can also be absorbed in the outer parts of the core. The presence of a central dip in the H$_2$D$^+$ profile of at least four spectra across the L1544 map (see Fig. 3) favors this scenario.

Figure 4 shows the integrated intensity map ($\int T_{mb} dv$) of ortho-H$_2$D$^+$ and para-D$_2$H$^+$ transitions, together with maps of N$_2$H$^+$ and N$_2$D$^+$ obtained by Caselli et al. (2002b) and the 1.3 mm continuum emission map of Ward-Thompson et al. (1999), smoothed to a resolution of 22$\prime$. We note the close similarity between the H$_2$D$^+$ and the N$_2$D$^+$ maps, and this is discussed in §3. In this paper, we studied the chemistry using the maps made by Caselli et al. (2002b) in H$^3$CO$^+$, HC$^{18}$O$^+$, DCO$^+$, D$^3$CO$^+$, C$^{17}$O, and C$^{18}$O with the IRAM 30 m telescope.

### 3. COLUMN DENSITY AND ABUNDANCE DETERMINATIONS

The observed molecular ions maps presented in Figure 4 show a general correlation, despite different beamwidths, with the distribution of dust continuum emission, in contrast to C$^{18}$O (1–0) and C$^{17}$O (1–0) (Caselli et al. 1999), which give clear evidence for depletion of CO at positions close to the continuum peak. H$_2$D$^+$ (1$^{10}$–1$^{11}$), N$_2$D$^+$ (2–1), and, to a lesser spatial extent, N$_2$H$^+$ (1–0) appear to trace the dust continuum. From these maps N$_2$H$^+$ does not seem to be depleted at the dust peak position.

In order to compare the observed species and put constraints on chemical models, we need to infer the column densities and abundances of H$_2$D$^+$ and D$_2$H$^+$, defined as $N(i)/N(H_2)$ for a generic species $i$, with $N(H_2)$ derived from the 1.3 mm dust continuum emission map of Ward-Thompson et al. (1999). Assuming LTE conditions, we can estimate the optical depth at the line center from the observed line intensities,

$$ T_{mb} = |J_a(T_{ex}) - J_\nu(T_{bg})|(1 - e^{-\tau}), $$

where $J_a(T) = (h\nu/k)/(e^{h\nu/kT} - 1)$ is the radiation temperature of a blackbody at a temperature $T$ and $T_{bg}$ is the cosmic background temperature of 2.7 K. The column density is then given by

$$ N_{tot} = \frac{8\pi\nu^3}{c^3} \frac{Q(T_{ex})}{g_u A_{ul}} \frac{e^{E_u/T_{ex}}}{e^{h\nu/kT_{ex}} - 1} \int \tau dv, $$

where $Q(T_{ex})$ is the partition function,

$$ Q(T_{ex}) = \sum_{i=0}^{\infty} (2i+1) \exp(-E_i/kT_{ex}). $$

In the case of the H$_2$D$^+$ transition, $g_u = 9$, $A_{ul} = 1.04 \times 10^{-4}$ s$^{-1}$, $E_{ul} = 17.9$ K; in the case of the D$_2$H$^+$ transition, $g_u = 9$, $A_{ul} = 4.55 \times 10^{-4}$ s$^{-1}$, $E_{ul} = 33.2$ K. Using equation (4), we can estimate the upper limit on the D$_2$H$^+$ main-beam temperature, under the assumption that the conditions of LTE are valid. With an excitation temperature of 8 K, the maximum main-beam temperature reaches 0.53 K, which is about the observed main-beam temperature of the D$_2$H$^+$ tentative detection, in the case where...
the spatial extent is larger than the beam size of 11″. The derived column densities depend on the assumed value of the excitation temperature. Within the 7–9 K temperature range, the column density at the dust peak can vary by a factor of 2. At larger distance, considering the increasing kinetic temperature and the decreasing molecular hydrogen density, the excitation temperature could be as low as 6 K. However, at these positions, the H$_2$D$^+$ column densities should only be decreased by a factor $\approx 2.5$. Consequently, we used a constant $T_{\text{ex}}$ for our observations as an approximation. The corresponding line parameters and column densities are presented in Table 1. The upper limit on the para-D$_2$H$^+$ column density has been calculated using the thermal line width at 8 K (0.27 km s$^{-1}$).

At the (0″, 0″) position, the column densities of ortho-H$_2$D$^+$ and para-D$_2$H$^+$ are $1.8 \times 10^{13}$ and $< 2.3 \times 10^{13}$ cm$^{-2}$, respectively (see Table 1). The abundances of species $i$, $X(i)$, have been determined dividing the column densities $N(i)$ by the associated H$_2$ column density derived from the 1.3 mm dust continuum emission. At the dust peak, we obtain $X(\text{ortho-H}_2\text{D}^+) \approx 1.5 \times 10^{-10}$ and $X(\text{para-D}_2\text{H}^+) < 1.8 \times 10^{-10}$.

We present in Figure 6 the variation of the observed ortho-H$_2$D$^+$, CO, H$_2$, HCO$^+$, HCO$^+$, N$_2$H$^+$, and N$_2$D$^+$ column densities (crosses) across the core (as a function of the impact parameter, the projected distance from the dust peak), as well as an upper limit on the para-D$_2$H$^+$.

Fig. 3.—Map of the H$_2$D$^+$ (1$_{00}$–1$_{11}$) line centered on the dust peak of L1544. The Y-axis represents the main-beam temperature. The position is indicated in arc-seconds in right ascension and declination offsets from the central position, on the top left of each spectrum. The reference for the velocity center at the (0″, 0″) position (7.28 km s$^{-1}$) is indicated by dashed lines.
estimate the total \( H_2D^+ \) column density or abundance because of the large uncertainty on this ratio. A more thorough discussion of the ortho-to-para ratio for \( H_2D^+ \) and D\(_2\)H\(^+\) is presented in §4.2.2. The observed column densities have then been averaged within the ranges delimited by the vertical dashed lines, at the positions \((2i + 1) \times 10^6\), where \( i = 0, 1, 2, 3, \ldots \), represented by triangles. The same computation was performed to present in Figure 7 the variation of the abundances as a function of the distance to the core center, limited to the central 70\' (\( r \approx 9800 \) AU). In §4.1 we compare these observations with the result from a best-fit model (dot-dashed lines).

From Figures 6 and 7, we see that only CO is strongly depleted in the core center. Note that in the CO column density computation we used \(^{16}\)O/\(^{18}\)O = 560 (Wilson & Rood 1994) and \(^{16}\)O/\(^{15}\)O = 4 (Wouterloot et al. 2005; Ladd 2004). Defining the CO depletion factor, \( f_D \), as the ratio of the CO “canonical” abundance \((\left< CO \right>/\left< H_2 \right>) = 9.5 \times 10^{-5}\); Frerking et al. 1982) and the observed CO abundance \([\text{CO}]/[\text{H}_2] \), Caselli et al. (1999) found \( f_D = 10 \) toward the dust peak and concluded that the most likely explanation for the low CO abundance is the freezeout of CO onto dust grains at high densities (\( n > 10^5 \) cm\(^{-3}\)). The corresponding radius of the depleted region is \( r \sim 6500 \) AU (\( \sim 45'' \)).

The CO abundance is a critical parameter in the deuteration of the molecular ion \( H_2^+ \) (see Fig. 1). In fact, from the abundance profiles presented in Figure 7 it is clear that the degree of deuterium enrichment (with D\(^{16}\)O, \( N_2D^+ \), and H\(^{2}D^+\)) increases toward the dust peak emission of L1544, where CO is highly depleted, as previously found by Caselli et al. (2002c). \( N_2H^+ \) does not show any signs of depletion. It is mainly formed by interaction between H\(^{3}\) and molecular nitrogen, which is likely to be the main repository of nitrogen in the gas phase. \( N_2 \) is only slightly less volatile than CO (a factor of \(< 0.9\); Öberg et al. 2005), so that the two neutrals are expected to behave similarly. However, \( N_2H^+ \) is destroyed by CO (Bergin et al. 2001, 2002; Pagani et al. 2005; Aikawa et al. 2005), so that the CO freezeout implies a drop in the destruction rate of \( N_2H^+ \), which at least partially balances the lower formation rate due to the \( N_2 \) freezeout (see also Aikawa et al. [2001] for a discussion on this point).

In fact, \( N_2H^+ \) is observed to survive in the gas phase at higher densities (\(< 10^5 \) cm\(^{-3}\)) compared to CO (\(< 10^4 \) cm\(^{-3}\)). This is also confirmed by the deuteration fractionation observed in \( N_2H^+ \)
(\sim 0.2), about 5 times larger than that measured in HCO\(^+\) (Caselli et al. 2002c). HCO\(^+\) is mainly formed via H\(^2\)+CO and destroyed by dissociative recombination, so that its abundance is simply reduced by the freezeout of CO, its parent species. From Figure 7 it seems that the HCO\(^+\) abundance is reduced at the dust peak and increases at larger distance.

3.1. Correlations

In Figure 8, we show the correlation between the ortho-H\(_2\)D\(^+\) abundances at the 0\(^0\), ±20\(^\circ\), and ±40\(^\circ\) distance from the dust peak and the CO depletion factor, the DCO\(^+\)/HCO\(^+\) ratio, and the N\(_2\)D\(^+\)/N\(_2\)H\(^+\) ratio. As intuitively expected, the ortho-H\(_2\)D\(^+\) abundance appears to be well correlated with the CO depletion factor (see Fig. 1). Also, the degree of deuterium enhancement in the HCO\(^+\) and N\(_2\)H\(^+\) molecules (measured from the DCO\(^+\)/HCO\(^+\) and N\(_2\)D\(^+\)/N\(_2\)H\(^+\) ratios) increases linearly with the ortho-H\(_2\)D\(^+\) abundance. The \(\chi^2\) parameter is calculated for the three points where the impact parameters are 0\(^0\), 20\(^\circ\), and 40\(^\circ\),

\[ \chi^2 = \sum_{i=0}^{2} \frac{(X_{\text{obs}}(i) - X_{\text{fit}})^2}{\sigma_{X_{\text{obs}}(i)}^2} \]

where \(X_{\text{obs}}\) and \(X_{\text{fit}}\) are the observed and fit values of the abundance, respectively, and \(\sigma_{X_{\text{obs}}(i)}\) is the uncertainty in \(X_{\text{obs}}\). The associated probabilities are reported when a correlation is established. The surprisingly high confidence level for the correlations between H\(_2\)D\(^+\) and the degree of deuteration in the HCO\(^+\) and N\(_2\)H\(^+\) molecules (\sim 100%), confirms that H\(_2\)D\(^+\) dominates the fractionation of these molecules at low temperatures.

4. CHEMICAL MODELING

In this section we interpret the observations using chemical models. We adopt a two-way strategy. First (in \S 4.1), we use a full chemical model applied to a density structure derived from continuum observations to produce an overall fit to all line observations presented in \S 3.2 and 3. In a second step (\S 4.2), we use a simplified chemical model focusing on the chemistry of H\(_3^+\) deuteration, in order to better understand the relation between CO depletion and deuteration and even to provide some estimates of the ortho-to-para ratio in the deuterated forms of H\(_3^+\) that can be derived from our observations.

4.1. The Best-Fit Model

To more quantitatively understand the column density and abundance correlations shown in Figures 6 and 7 we used the model described in Caselli et al. (2002c), updated so that it now includes the multiply deuterated forms of H\(_3^+\) (as in Crapsi et al. 2005) and new values of the binding energies of CO and N\(_2\), following the measurements by Oberg et al. (2005), as well as other modifications, to better account for the physical structure of the core. Briefly, the model considers a spherically symmetric cloud, with the density gradient as derived by Tafalla et al. (2002), using the 1.3 mm dust continuum emission data from Ward-Thompson et al. (1999), where the central density is \(n(H_2) = 1.4 \times 10^6\) cm\(^{-3}\) (see Fig. 5). The temperature profile has been included, using the recent findings of Young et al. (2004), where the temperature is about 7.5 K at the center and reaches about 12 K at the edge (see Fig. 5). The chemical network contains CO, O, and N\(_2\), which can freeze out onto dust grains and desorb due to cosmic-ray impulsive heating (as in Hasegawa & Herbst 1993). The initial abundances are \(X_0(\text{CO}) = 9.5 \times 10^{-5}\) (cf. Frerking et al. 1982), \(X_0(N_2) = 4.0 \times 10^{-5}\) (slightly smaller than \(6.6 \times 10^{-5}\), the cosmic value from Snow & Witt [1996], assuming that all nitrogen is in molecular form), and \(X_0(O) = X_0(\text{CO})/2\), a factor of 2 less than what is typically found in gas-phase–only chemical models (e.g., Lee et al. 1996). The abundances of the molecular ions (N\(_2\)H\(^+\), H\(_3^+\)O\(^+\), HCO\(^+\), and their deuterated forms) are calculated in terms of the instantaneous abundances of neutral species, assuming that the timescale for ion chemistry is much shorter than that for freezeout. The electron fraction has been computed as described in Caselli et al. (2002c), using a simplified version of the reaction scheme of Umeyabasy & Nakano (1990), where the chemistry of a generic molecular ion “mH\(^+\)” is taken into account, assuming formation due to proton transfer with H and destruction by dissociative recombination with electrons and recombination on grain surfaces (using rates from Draine & Sutin 1987). The “MRN” grain size distribution has been used (Mathis et al. 1977). We adopted the rate coefficients for the proton-deuteron exchange reactions recently measured by Gerlich et al. (2002). The model is run until the column density of C\(^1\)\(^1\)\(_2\) toward the core center reaches the observed value [N(C\(^1\)\(^1\)\(_2\)) = 6 \times 10^{14}\) cm\(^{-2}\); Caselli et al. 2002c].

The best-fit parameters of the model, which best reproduce the observed molecular column densities at the dust peak and the observed column density and abundance profiles, are the following:

1. A cosmic-ray ionization rate of \(\zeta = 1.3 \times 10^{-17}\) s\(^{-1}\), a standard value, typically used in chemical models (since Herbst & Klemperer 1973).
2. Binding energies for CO and N\(_2\) of \(E_B(\text{CO}) = 1100\) K and \(E_B(N_2) = 900\) K, values close to the binding energies measured for CO on water ice (Collings et al. 2003)—the ratio between N\(_2\) and CO binding energies (0.8) being comparable to the value (0.9) recommended by Oberg et al. (2005).
3. A binding energy for atomic oxygen of \(E_B(O) = 750\) K, used in current gas-grain chemical models (e.g., Aikawa et al. 2005).
4. A minimum size of the dust grains, in the MRN distribution of \(a_{\text{min}} = 5 \times 10^{-6}\) cm (10 times larger than in MRN).
5. A sticking coefficient of \(S = 1.0\) (Burke & Hollenbach 1983).
6. An initial abundance of metals (assumed to freeze out with a rate similar to that of CO) of \(X(M^+) = 10^{-7}\).
Fig. 6.—Variation of the CO (in a 20′ beam), H$_{2}$, HCO$^+$, DCO$^+$, N$_{2}$H$^+$, N$_{2}$D$^+$, H$_{2}$D$^+$, and D$_{2}$H$^+$ column densities as a function of distance. The cross represents the observation points and the 3σ error, the triangles represent the observation points averaged in the bins delimited by the dashed lines, and the dot-dashed lines represent the results from a best-fit model. For H$_{2}$D$^+$, note that the variation of the observed ortho column density is compared with the modeled ortho variation (see text). Also for D$_{2}$H$^+$, the upper limit on the para column density is reported on the plot of the modeled ortho-para variation.
Fig. 7.—Variation of the CO (in a 20° beam), HCO⁺, DCO⁺, N₂H⁺, N₂D⁺, H₂D⁺, and D₂H⁺ abundances as a function of distance. The triangles represent the observation points averaged in the bins delimited by the dashed lines, and the dot-dashed lines represent the results from a best-fit model. For H₂D⁺, note that the variation of the observed ortho abundance is compared with the modeled ortho variation (see text). Also for D₂H⁺, the upper limit on the para abundance is reported on the plot of the modeled ortho+para variation.
In Figures 6, 7, and 8 we overlaid the results from the best-fit model (dashed lines) on the observations. For the H2D+ plots, we present the ortho-H2D+ observation points and scaled the total-H2D+ result from the model by 2.3, the factor between the predicted and the observed value at the dust peak position (assumed constant across the core). From this, an ortho-to-para ratio of ~0.8 can be deduced for H2D+, but, considering the uncertainties associated with this parameter (e.g., Pagani et al. 1992; Flower et al. 2005), we postpone a discussion on this topic until § 4.2, where a parameter space exploration is presented. For the D2H+ plot, we present the upper limit on the observed para-D2H+ compared to the (total) D2H+ result from the model. The ortho-H2D+ column densities and abundances observed at 0", ±20", and ±40" are well reproduced by the model, within the error bars (see Figs. 6 and 7). Note that although we need to assume a high degree of CO depletion in order to explain the CO observations, it appears that the HCO+ column density is slightly underestimated for the model at the dust peak emission. However, the strong variation (factor of 2) seen in Figure 6 between 0" and 15" could decrease the central HCO+ column density. The discrepancy between the HCO+ and DCO+ column densities at larger distances can be explained by the uncertainties on the optical depth, since the less optically thick isotopes (HC18O+ and D13CO+) have only been used for the central position. The beam size for the HC18O+ observations is also larger (by 50%) than the 20" range.

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Some N2 depletion is needed in order to explain the N2H+ and N2D+ observations. Through the hyperfine structure of these species we can determine directly the optical depth in several transitions using the relative intensities of the hyperfine satellites. This considerably reduces the error in our computations, compared to other species such as HCO+ and DCO+.

This detailed model of the ion chemistry in L1544 simulates the observed depletion in the core center and can reproduce the observed dependency of the column densities and abundances of species such as N2H+, N2D+, HCO+, and DCO+ as a function of the impact parameter. This allows us to separately discuss the relative contributions from the high-density depleted core and the lower density foreground (and background) gas.

### 4.2. Chemical Parameter Space Exploration

In order to focus and analyze in detail the H2D+ chemistry, we performed a parameter study using a model that computes the deuterated forms of H2 as a function of some key parameters, such as the grain size, the age of the L1544 condensation, and the cosmic-ray ionization rate. This method has the advantage of concentrating on the H2D+ chemistry to avoid reproducing other molecular observations. Before discussing the comparison of the theoretical predictions with the observations, we give a short description of the model used.

It is an adaptation of the Ceccarelli & Dominik (2005) model, which has been developed for the protoplanetary disks. It computes the H3+, H2D+, D2H+, and D3+ abundances in cold and dense gas. Since the involved temperatures (≤30 K) and densities (≥106 cm⁻³) are very similar to those found around L1544, the model can be used directly, by just changing the geometry. For an easy and straightforward comparison with the observations, we compute the H3+ chemistry in a gas cube with a given density and temperature. The relative abundances of the H3+ deuterated forms are computed by solving the charge equilibrium equations and the deuterium chemistry equations.

In this model we also consider grains as a possible source of H2D+, H2D+, D2H+, and D3+ destruction. In practice, the larger the CO depletion, the larger the H2D+/H2+ and D2H+/H2D+ ratios.

Two factors (other than the dust temperature) can modify the CO depletion, namely, the age of the condensation (larger ages give larger CO depletions because the molecules have more time to freeze out onto the grains) and the gas density (the condensation rate is proportional to the gas density). In addition, the cosmic-ray ionization rate regulates the overall ionization degree in the condensation and therefore the H3+ isotopomers abundances. Finally, the grain sizes enter both in the CO condensation rate (via the grains area) and in the charge balance, because negatively charged grains recombine with the positively charged molecular ions. In this model, we adopted the same parameters (binding energy for CO and N2 and the sticking coefficient) chosen for our best-fit model (see § 4.1).

#### 4.2.1. H2D+ and D2H+ versus CO Depletion

In Figure 9, we present the results of the model, varying the three key parameters of the model (cosmic ionization rate, the grain radius, and the age of the core) in order to reproduce the total (ortho+para) H2D+ and D2H+ abundances. We plot the abundances as a function of depletion, because this parameter is more directly observed (via CO column density and dust continuum observations) than the gas density. We also make a comparison with
the observations of ortho-H$_2$D$^+$ and para-D$_2$H$^+$ to get an insight into the deuterium chemistry of H$_3^+$. We fixed the temperature of the cloud in the model to 8 K, which is within the range found from molecular and dust measurements. For comparison we also ran the cases with a temperature of 10 K and did not find any substantial difference. The free-fall time is approximately $3 \times 10^4$ yr for a density of about $10^6$ cm$^{-3}$. In presence of a magnetic field, the collapse time is about an order of magnitude larger (Ciolek & Basu 2000). We vary the age between $10^4$ and $10^6$ yr, the latter being close to the lifetime of a starless core. In our calculations, we assumed all grains in the cloud have the same size, but we investigated the result for different values of the grain radius. A grain size of 0.1 $\mu$m is the typical value assumed in chemical models for the interstellar medium, where it follows the MRN distribution. In the upper plot of Figure 9 we used a standard cosmic ionization rate of $3 \times 10^{-16}$ s$^{-1}$ and a typical age of $10^5$ yr and varied the dust grain average sizes between 0.05 and 0.4 $\mu$m. In the middle plot we fixed the age to $10^5$ yr and the grain size to 0.1 $\mu$m and varied the cosmic ionization rate between $3 \times 10^{-18}$ and $3 \times 10^{-16}$ s$^{-1}$. In the lower plot we fixed the grain size to 0.1 $\mu$m and the cosmic ionization rate to $3 \times 10^{-17}$ s$^{-1}$ and varied the age between $10^4$ and $10^6$ yr.

Fig. 9.—Variation of the H$_2$D$^+$ and D$_2$H$^+$ abundances for the model (solid line) as a function of CO depletion factor. The points with the corresponding error bars represent the observed abundances of ortho-H$_2$D$^+$ and para-D$_2$H$^+$ toward L1544, whereas the lines show the modeled abundances of the ortho+para states. Hence we expect the observed values to lie below the modeled ones. The temperature was fixed at 8 K. In the upper plot we varied the grain size: 0.05, 0.1, 0.2, 0.3, and 0.4 $\mu$m. Note that increasing the grain size decreases the H$_2$D$^+$ and D$_2$H$^+$ abundances (see text). In the middle plot we varied the cosmic ionization rate: $3 \times 10^{-16}$ (solid line), $3 \times 10^{-17}$ (dashed line), and $3 \times 10^{-18}$ s$^{-1}$ (dot-dashed line). In the lower plot we varied the age of the cloud: $10^4$ (solid line), $10^5$ (dashed line), and $10^6$ yr (dot-dashed line).
of the cloud between $10^4$ and $10^6$ yr. The observation points (or upper limit in the case of D$_2$H$^+$) and their corresponding error bars are superimposed in these plots, ortho-H$_2$D$^+$ on the left side and para-D$_2$H$^+$ on the right side.

As the grain size increases while the total grain mass is conserved, the abundance of grains relative to H$_2$ decreases $\propto a_{\text{grain}}^{-3}$, and also the grain surface area per H$_2$ decreases $\propto a_{\text{grain}}^{-1}$. This effect slows down the freezout of CO, the same CO depletion is therefore reached either after a longer time or at a higher density. Since we keep the age constant, the effect of the density is observed in Figure 9; larger grain sizes correspond to higher densities, at which the overall degree of ionization is smaller. Since H$_2$D$^+$ is the dominant ion, this is directly mirrored in the H$_2$D$^+$ abundance. Also, decreasing the cosmic ionization rate leads to a decrease in the abundances. Indeed, H$_2^+$ ions (and consequently their deuterated forms) are formed by the ionization of H$_2$ due to cosmic rays. And finally, increasing the age of the cloud will increase their abundances, as the CO depletion rate is time dependent. Consequently, for a more evolved cloud the same CO depletion is achieved for lower densities, corresponding to a higher degree of ionization, which is again directly reflected in the H$_2$D$^+$ and D$_2$H$^+$ abundances.

4.2.2. The Ortho and Para Forms

Both H$_2$D$^+$ and D$_2$H$^+$ molecules have ortho and para forms, corresponding to the spin states of the protons (for H$_2$D$^+$) or deuterons (for D$_2$H$^+$). In order to compare the modeled abundances with the observations of one spin state only, it is critical to know the ortho-to-para ratio for these two molecules. Under LTE conditions, at temperature $T$, the relative populations of the lowest ortho ($1,1$) and para ($0,0$) levels of H$_2$D$^+$ would be

$$n(1,1) \over n(0,0) = 9 \exp \left( - {86.4 \over T} \right),$$

and the relative populations of the lowest ortho ($0,0$) and para ($1,1$) levels of D$_2$H$^+$ would be

$$n(1,1) \over n(0,0) = {1 \over 6} \exp \left( - {50.2 \over T} \right).$$

With these formulae, at 8 K, the H$_2$D$^+$ ortho-to-para ratio would be $\approx 1.8 \times 10^{-4}$, and the D$_2$H$^+$ para-to-ortho ratio would be $\approx 2.8 \times 10^{-3}$. The ortho form of H$_2$D$^+$ is produced mainly in reactions of the para form with ortho-H$_2$ (e.g., Gerlich et al. 2002). Therefore, its high o/p ratio is attributable to the relatively high ortho-H$_2$ abundance as first noted by Pagani et al. (1992). Because the o/p ratio is not thermalized at the low temperature considered here, the o/p H$_2$D$^+$ ratio is not thermalized either. This can be illustrated in the Flower et al. (2004) model, where at temperatures lower than 10 K a hydrogen density of $2 \times 10^6$ cm$^{-3}$ and a grain size of 0.1 $\mu$m, the o/p-H$_2$D$^+$ reaches unity and the p/o-D$_2$H$^+$ value is about 0.1. Increasing the grain size will decrease the grain surface, leading to a decrease of the H$_2$ formation rate. Therefore, the H$_2$ ortho-to-para ratio will obviously decrease, as well as the H$_2$D$^+$ ortho-to-para ratio.

From our observations we find that para-D$_2$H$^+$/ortho-H$_2$D$^+$ is less than 1.3 at the dust peak emission assumed to be at 8 K. In the prestellar core 16293E (Vastel et al. 2004) we measured a para-D$_2$H$^+$/ortho-H$_2$D$^+$ ratio of 0.75 for an excitation temperature of 10 K. We also computed the H$_2$D$^+$ ortho-to-para ratio and an upper limit on the D$_2$H$^+$ para-to-ortho ratio by comparing the observed abundances of ortho-H$_2$D$^+$ and para-D$_2$H$^+$ with the total (ortho+para) abundances of H$_2$D$^+$ and D$_2$H$^+$, as calculated using the model described in § 4.2.1. In Table 2, the ortho-to-para ratio for H$_2$D$^+$ and the para-to-ortho ratio for D$_2$H$^+$ are quoted in order to reproduce the values obtained by the model for different sets of parameters, which are the cosmic ionization rate, the age of the core, and the grain radius. We can directly compare our results on H$_2$D$^+$ with the Flower et al. (2004) model, even if their study assumes complete depletion (i.e., that CO abundance should be less than $10^{-6}$). Indeed, the abundance of both ortho and para spin states of H$_2$D$^+$ depends on the ortho and para forms of molecular hydrogen (through the proton-exchanging reaction of H$_2^+$ with H$_2$ followed by reaction 1), which does not vary as a function of depletion. On the contrary, the abundance of both para and ortho forms of D$_2$H$^+$ is determined by reactions with HD (produced on the grain surfaces) and will therefore depend on the core depletion. The Flower et al. model predicts H$_2$D$^+$ ortho-to-para ratios larger than the maximum value of 0.3 we observed for a temperature of 8 K and a H$_2$ density of $2 \times 10^6$ cm$^{-3}$ (G. Pineau des Forêts 2005, private communication), spanning ranges up to 0.4 $\mu$m of the grain radius. As a consequence, since the H$_2$D$^+$ ortho-to-para ratio decreases as a function of the grain radius, it is likely that this should be larger than 0.3 $\mu$m. This depletion of small grains in this core is consistent with grain coagulation, since ice condensation is not enough to increase the grain radius.

| Cosmic Ionization Rate (s$^{-1}$) | Core Age (yr) | Grain Radius (\(\mu\)m) | (o/p) H$_2$D$^+$ | (p/o) D$_2$H$^+$ |
|----------------------------------|--------------|----------------|-----------------|----------------|
| $3 \times 10^{-17}$ | $10^5$ | 0.05 | 0.02 | <1.07 |
| $3 \times 10^{-17}$ | $10^5$ | 0.1 | 0.03 | <0.15 |
| $3 \times 10^{-17}$ | $10^5$ | 0.2 | 0.08 | <0.55 |
| $3 \times 10^{-16}$ | $10^5$ | 0.1 | 0.03 | <0.29 |
| $3 \times 10^{-17}$ | $10^5$ | 0.1 | 0.07 | <0.29 |
| $3 \times 10^{-17}$ | $10^5$ | 0.1 | 0.03 | <0.29 |
| $3 \times 10^{-17}$ | $10^5$ | 0.3 | 0.17 | <0.63 |
| $3 \times 10^{-18}$ | $10^5$ | 0.4 | 0.32 | No solution |
| $3 \times 10^{-18}$ | $10^5$ | 0.4 | 0.33 | <11.81 |
| $3 \times 10^{-17}$ | $10^5$ | 0.4 | 0.33 | <11.81 |
### Table 3
**Current and Future Facilities for the Chemistry of H$_2$D$^+$ and D$_2$H$^+$ in Prestellar Cores, Protoplanetary Disks, and Protostars**

| Name            | Aperture | Platform          | Available | $I_{1,0}^{}$ – $I_{1,1}^{}$ (372.4 GHz) | $I_{1,0}^{}$ – $I_{0,0}^{}$ (1.37 THz) | $I_{1,0}^{}$ – $I_{0,1}^{}$ (691.7 GHz) | $I_{1,1}^{}$ – $I_{0,0}^{}$ (1.48 THz) |
|-----------------|----------|------------------|-----------|---------------------------------------|--------------------------------------|--------------------------------------|--------------------------------------|
| CSO             | 10.4 m   | Mauna Kea (USA)  | Y         | Y                                     | N                                    | Y                                    | N                                    |
| JCMT            | 15 m     | Mauna Kea (USA)  | Y         | HARP B                                | N                                    | Y                                    | N                                    |
| SOFIA           | 2.5 m    | Airborne (747)   | 2007      | Casimir, GREAT (CONDOR)              | Casimir, GREAT (CONDOR)              | Y                                    | Y                                    |
| Herschel (HIFI) | 3.5 m    | Space (L2)       | 2007      | N                                     | N                                    | Y                                    | Y                                    |
| ALMA            | 50 m x 12 m | Atacama (Chile) | 2010      | Y                                     | N                                    | Y                                    | N                                    |
| APEX            | 12 m     | Atacama (Chile)  | 2005–2006 | CONDOR                                | CONDOR                               | Y                                    | CONDOR                               |
5. CONCLUSIONS AND PERSPECTIVES

In this paper we studied the prestellar core L1544, focusing on the H$_2$D$^+$ chemistry throughout the cloud. It is now widely accepted that the H$_2$D$^+$ molecule is the main tracer of the CO-depleted prestellar cores, and we point out in this paper that the H$_2$D$^+$ emission is extended (over 60$''$) and an excellent tracer of the dust continuum, with an emitting radius of about 7000 AU in the case of L1544. Hence, the line profile of this molecule would provide a crucial guide to the dynamical behavior of the high-density core. It is likely that the double-peaked profile found in the central position, as well as positions around, is broadened by the central infall and is absorbed in the outer parts of the core (van der Tak et al. 2005).

We first used a model of the ion chemistry, coupled with the physical structure of the core of L1544, including the deuterated isotopologues of the H$_3^+$ ion. This simulates the observed depletion and can approximately reproduce the observed dependence of the column densities of species such as N$_2$H$^+$, N$_2$D$^+$, HCO$^+$, DCO$^+$, and H$_2$D$^+$ as a function of radius.

This study reveals a correlation between the ortho-H$_2$D$^+$ abundance and (1) the CO depletion factor, (2) the degree of deuteration in the HCO$^+$ molecule, and (3) the degree of deuteration in the N$_2$H$^+$ molecule. H$_2$D$^+$ will survive longer, at higher density than N$_2$H$^+$ and N$_2$D$^+$.

We then used a simpler model focusing on the H$_2$D$^+$ chemistry, in which we did a wide parameter study. We discuss how the H$_2$D$^+$ and D$_2$H$^+$ abundances depend on the cosmic ionization rate, the age of the core, and the grain radius by varying these parameters. It appears that the most important parameter to reproduce the observed values is the grain radius, as small grains accelerate the freezeout of CO and the observed values are consistent with a freezeout rate dominated by larger grains. Therefore, we found that to reproduce the observations we need a larger grain radius of 0.3 μm.

This study can be considered a springboard for observations to come, since the current observations are limited by the poor atmospheric transmission at the relevant frequencies. Table 3 lists some of the major telescopes and interferometers that can be used for the study of H$_2$D$^+$ chemistry in prestellar cores, protoplanetary disks, and protostars. Probably, D$_2^+$ cannot be observed, because enhanced D$_2^+$ abundance implies very cold and very dense regions. Since D$_2^+$ is a symmetric molecule, it does not have rotational transitions and does have its bending modes in the near-infrared. Therefore, these transitions will only be observable in absorption against a strong near-infrared continuum. H$_2$D$^+$ and D$_2$H$^+$ are hence the only tracers of cold, dense phases of molecular clouds prior to star formation.

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