Chemistry and kinematics of the pre-stellar core L1544: Constraints from H$_2$D$^+$. 

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This paper explores the sensitivity of line profiles of H$_2$D$^+$, HCO$^+$ and N$_2$H$^+$, observed towards the center of L 1544, to various kinematic and chemical parameters. The total width of the H$_2$D$^+$ line can be matched by a static model and by models invoking ambipolar diffusion and gravitational collapse. The derived turbulent line width is $b\approx0.15$ km s$^{-1}$ for the static case and $\lesssim0.05$ km s$^{-1}$ for the collapse case. However, line profiles of HC$^{18}$O$^+$ and N$_2$H$^+$ rule out the static solution. The double-peaked H$_2$D$^+$ line shape requires either infall speeds in the center that are much higher than predicted by ambipolar diffusion models, or a shell-type distribution of H$_2$D$^+$, as is the case for HCO$^+$ and N$_2$H$^+$. At an offset of $\approx20''$ from the dust peak, the H$_2$D$^+$ abundance drops by a factor of $\approx5$.

1 Introduction

Deuterium-bearing molecules are important as probes of the very cold phases of molecular clouds prior to star formation. The H$_2$D$^+$ ion is especially important as tracer of H$_3^+$, the primary ion in dense molecular clouds, which does not have a dipole moment and hence no pure rotational lines. In addition, at low temperatures ($\lesssim10$ K), H$_2$D$^+$ has the ability to channel D atoms from their main reservoir, HD, into heavier species. This process leads to abundance ratios of DCO$^+$/HCO$^+$ and N$_2$D$^+$/N$_2$H$^+$ of $\sim10^{-3} - 10^{-1}$ observed towards dense cores, much larger than the elemental D/H ratio of $\sim10^{-5}$. Recent observations of multiply deuterated H$_2$CO, CH$_3$OH, H$_2$S and NH$_3$ (see Ceccarelli, this volume) suggest that under extreme conditions, a significant fraction of D may be transferred to heavy molecules. We wish to quantify the role of H$_2$D$^+$ in this process, and compare with other processes such as grain surface reactions (Caselli, this volume).

The ground-state J$_{101}$–0$_{00}$ transition of para-H$_2$D$^+$ at 1370 GHz will be a prime target for GREAT on SOFIA. However, with the upper energy level
65 K above ground, this line will only be excited in relatively warm (≥ 20 K) regions, where chemical fractionation is ineffective. For colder sources, the 1_{10−11} ground-state transition of ortho-H_2D^+ at 372 GHz is more suitable, which can be observed from the ground under good conditions. At the low temperatures (≤ 10 K) and high densities (> 10^5 cm^-3) of pre-stellar cores, reactive collisions with ortho-H_2 keep the ortho-para ratio of H_2D^+ at ~1, orders of magnitude above the LTE value [1, 2].

Until 2002, only two detections of H_2D^+ had been obtained, which indicated abundances of ~10^{-11}−10^{-12} towards Class 0 objects [3, 4]. In October 2002, we [5] observed strong H_2D^+ emission towards the pre-stellar core L 1544, and derived an abundance of ~1×10^-9 in the central ∼20″. Such a high abundance suggests that in this region, all CNO-bearing species are depleted onto dust grains, a situation explored in more detail by Walmusley (this volume). Data taken in June 2003 at the CSO indicate that the same phenomenon takes place in at least five other pre-stellar cores. More observations are scheduled for December 2003. These data will be presented in a forthcoming paper. Here we investigate the line profile of H_2D^+ in L 1544, and derive its abundance outside the central region.

2 Kinematics

The line profile of H_2D^+ towards L 1544 appears double-peaked, although the signal-to-noise ratio is not high (Fig. 1). Fitting two Gaussians to the profile yields results very similar to those for the profiles of HC^{18}O^+, D^{13}CO^+ and N_2H^+, observed by [6]: two thermal components separated by ∼0.26 km s^-1 (Table 1). We therefore investigate whether the kinematic models that fit the HCO^+ and N_2H^+ data also reproduce the H_2D^+ line profile.

Table 1. Centroids and widths of the two velocity components. Numbers in brackets denote uncertainties in units of the last decimal.

| Line                | V_{LSR} | ∆V_{obs} | ∆V_T |
|---------------------|---------|----------|------|
|                     | km s^-1 | km s^-1  | km s^-1 |
| H_2D^+ (1_{10−11})  | 7.06(3) | 0.22(5)  | 0.28−0.34 |
|                     | 7.34(2) | 0.25(6)  |       |
| HC^{18}O^+ (1−0)    | 7.04(1) | 0.18(3)  | 0.10−0.12 |
|                     | 7.28(1) | 0.23(3)  |       |
| D^{13}CO^+ (2−1)    | 7.08(2) | 0.20(4)  | 0.10−0.12 |
|                     | 7.35(4) | 0.20(8)  |       |
| N_2H^+ (1−0, F_1 F=10−11) | 7.08(1) | 0.19(1)  | 0.11−0.13 |
|                     | 7.33(1) | 0.20(2)  |       |

* Thermal line width at T_{kin}=7 and 10 K.
The line profile of H$_2$D$^+$ was modeled using a Monte Carlo radiative transfer program [7] 5. Figure 2 shows the adopted temperature and density structure of L1544, taken from [8]. See [5] for details of the excitation model; at $T_{\text{kin}} \lesssim 10$ K, ortho-H$_2$D$^+$ is essentially a two-level system, so that our results are not sensitive to the collision rates of non-radiative transitions between high-lying levels. For H$_2$D$^+$ we adopt an abundance of $1 \times 10^{-9}$ in the central 20″ [5]. For HCO$^+$, DCO$^+$, N$_2$H$^+$ and N$_2$D$^+$, we used the abundance profiles from [9], Model 3, and assumed zero abundance inside $r=2500$ AU.

We explored static models, and models with velocity fields from the ambipolar diffusion models ‘t3’ and ‘t5’ of [10] (see [6] for details). For the turbulent broadening, Doppler parameters $b$ between 0.05 and 0.25 km s$^{-1}$ were tried. Smaller values of $b$ are overwhelmed by thermal broadening; larger ones do not fit the data.

We find that the total width of the H$_2$D$^+$ line can be matched using either velocity field. While the best-fit static model has $b=0.15$, $b=0.05$ gives the best fits with the infall velocity fields. However, the HC$^{18}$O$^+$ and N$_2$H$^+$ $J=1$-0 observations from [6] rule out the static model, which does not give a double-peaked line shape. Using the infall velocity fields, the data are matched with $b=0.05$, consistent with the H$_2$D$^+$ results (Fig. 1).

None of our adopted velocity fields reproduces the double-peaked H$_2$D$^+$ line shape that the observations indicate. One possibility is that the infall speeds of $\approx 0.1$ km s$^{-1}$ continue further inwards than in the models by [10]. Alternatively, the distribution of H$_2$D$^+$ may have a central hole, not because of adsorption onto dust grains (as for CO and N$_2$, the precursors of HCO$^+$ and N$_2$H$^+$), but due to conversion into D$_2$H$^+$ and D$_3^+$.

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5 http://www.mpifr-bonn.mpg.de/staff/fvandertak/ratran/
3 Abundance profile of H$_2$D$^+$

The abundance of H$_2$D$^+$ away from the dust peak of L 1544 was estimated to be a factor of two lower than toward the dust peak [5]. However, this abundance may be an overestimate because some fraction of the emission at the 20$''$ offset positions is pickup from the central core. We have run Monte Carlo models of the H$_2$D$^+$ emission, using the same temperature and density structure as before, and dropping the H$_2$D$^+$ abundance at a 20$''$ radius by factors of 2–10 from its central value of $1 \times 10^{-9}$. The H$_2$D$^+$ intensity at the 20$''$ offset position is best matched if the abundance drops by a factor of $\approx 5$ at this radius. This result is independent of the velocity field. Models where this factor is 3 or 10 produce clearly worse matches to the data.

In a future paper, we will follow our results up with two-dimensional models and an exploration of different velocity fields. We will also model line profiles at offset positions.

References

1. Pagani, L., Salez, M., & Wannier, P. G.: A&A, 258, 479 (1992)
2. Gerlich, D., Herbst, E., & Roueff, E.: Plan. Sp. Science, 50, 1275 (2002)
3. Stark, R., van der Tak, F. F. S., & van Dishoeck, E. F.: ApJ, 521, L67 (1999)
4. Stark, R., Sandell, G., Beck, S., et al.: ApJ, submitted (2003)
5. Caselli, P., van der Tak, F. F. S., Ceccarelli, C., & Bacmann, A.: A&A, 403, L37 (2003)
6. Caselli, P., Walmsley, C. M., Zucconi, A., Tafalla, M., Dore, L., & Myers, P. C.: ApJ, 565, 331 (2002)
7. Hogerheijde, M.R., & van der Tak, F. F. S.: A&A, 362, 697 (2000)
8. Galli, D., Walmsley, M., & Gonçalves, J.: A&A, 394, 275 (2002)
9. Caselli, P., Walmsley, C. M., Zucconi, A., Tafalla, M., Dore, L., & Myers, P. C.: ApJ, 565, 344 (2002)
10. Ciolek, G. E. & Basu, S.: ApJ, 529, 925 (2000)