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LETTER TO THE EDITOR

Detection of H_2D^+ in a massive prestellar core in Orion B*

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ABSTRACT

Aims. The purpose of this study is to examine the prediction that the deuterated H_3^+ ion, H_2D^+, can be found exclusively in the coldest regions of molecular cloud cores. This is also a feasibility study for the detection of the ground-state line of *ortho*-H_2D^+ at 372 GHz with APEX.
Methods. The ($1_{10} \rightarrow 1_{11}$) transition of H_2D^+ at 372 GHz was searched towards selected positions in the massive star forming cloud OriB9, in the dark cloud L183, and in the low- to intermediate mass star-forming cloud R CrA.
Results. The line was detected in cold, prestellar cores in the regions of OriB9 and L183, but only upper limits were obtained towards other locations which either have elevated temperatures or contain a newly born star. The H_2D^+ detection towards OriB9 is the first one in a massive star-forming region. The fractional *ortho*-H_2D^+ abundances (relative to H_2) are estimated to be $\sim 1 \times 10^{-10}$ in two cold cores in OriB9, and 3×10^{-10} in the cold core of L183.
Conclusions. The H_2D^+ detection in OriB9 shows that also massive star forming regions contain very cold prestellar cores which probably have reached matured chemical composition characterized, e.g., by a high degree of deuterium fractionation. Besides as a tracer of the interior parts of prestellar cores, H_2D^+ may therefore be used to put contraints on the timescales related to massive star formation.

Key words. ISM: clouds – ISM: molecules – ISM: individual objects: IRAS 05405-0117 – stars: formation – radio lines: ISM – telescopes

1. Introduction

The trihydrogen ion, H_3^+, is supposed to become the principal carrier of positive charge in the centres of cold, dense cores when "heavy" elements like C, O and N, are nearly completely depleted (Walmsley et al. 2004). Because deuterium fractionation reactions are favoured in cold gas, relatively large abundances of the isotopoloques H_2D^+ and D_2H^+ are to be expected in these objects. This has been also confirmed by observations (Caselli et al. 2003; Vastel et al. 2004). While infrared absorption spectroscopy of H_3^+ can be used to extract vital information on the gas columns towards infrared sources (e.g. McCall et al. 1999), the rotational lines of H_2D^+ and D_2H^+ probe the physical conditions of cold, prestellar cores. The abundance of H_3^+ and its deuterated forms depend on the cosmic ray ionization rate of H_2, and on the abundances of destructing agents: electrons, gaseous neutral species like CO and N_2, and negatively charged grains (e.g. Caselli et al. 2003; Walmsley et al. 2004). Furhermore, the H_3^+ abundance and the H_2D^+/H_3^+ abundance ratio depend heavily on the *ortho:para* ratio of H_2, which in turn is a function of time and density (Pineau des Forêts et al. 1991; Flower et al. 2006).

The ground-state ($1_{10} \rightarrow 1_{11}$) transition of *ortho*-$H_2D^+$ lies between adjacent atmospheric O_2 and H_2O absorption lines and its observation requires extremely good conditions. A reasonable limit is that the precipitable water vapour content of the atmosphere, PWV, is less than 0.5 mm, which can be achieved at high-altitude observatories only. H_2D^+ has been previously detected from Mauna Kea towards a protostellar core (Stark et al. 1999), and in a small number of prestellar dark cloud cores (Caselli et al. 2003; Stark et al. 2004; Vastel et al. 2006).

In this Letter we report on the first H_2D^+ observations with the Atacama Pathfinder Experiment, APEX, during its Science Verification periods in July, October and November 2005. The main goal of this series of observations was to test the feasibility of the 372 GHz line observations with this instrument. In the course of these measurements H_2D^+ was detected in a core belonging to a high-mass star forming region. This may open new vistas to the chemical evolution preceding the collapse of massive stars.

2. Source selection

The selection of targets contains five starless cores of molecular clouds and one massive, cold core which encloses a low-luminosity far-infrared source.

The massive, cold core **OriB9** embedding IRAS 05405-0117 in the region of Orion B is described in Caselli & Myers (1994), Caselli & Myers (1995), and Harju et al. (1993). The average ammonia linewidth is only 0.29 km s^{-1}. The core does not stand out on the ^{13}CO and C^{18}O maps of Caselli & Myers (1995),

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probably because of CO depletion. In this survey we have included the three $N_2H^+(1-0)$ peaks found by Caselli & Myers (1994). These are likely to pinpoint separate clumps within the core. The clump associated with the IRAS source is likely to represent an early stage of collapse at which newly born stars have not yet disturbed their surroundings. The subsidiary clumps (OriB9 E and N) may be in a still earlier, pre-collapse phase. Depending on the time spent in the pre-collapse phase, chemical evolution may have resulted in a high degree of depletion and an increased H_2D^+ abundance.

The two positions observed towards the nearby, starless dark cloud **L183** (L134N) (see e.g. Pagani et al. 2005, and references therein) correspond to the 450 μm continuum peaks in the SCUBA map of Kirk et al. (2005). The southern maximum (L183-S, the 850 μm emission peak) can be assigned to a very cold, dense core with a high degree of molecular depletion. The two sources may represent different evolutionary stages of prestellar cores (Lehtinen et al. 2003). Therefore, it is interesting to compare their chemical and dynamical properties. After perfoming these observations we learned that the H_2D^+ has been detected at several positions along the dense ridge of L183 with the CSO by Vastel et al. (2006).

The starless, dense clump **R CrA NW** in the northwestern part of the R Coronae Australis cloud lies close to the 1.2 mm continuum source "MMS10" (Chini et al. 2003). Our position corresponds to an ammonia peak (Harju et al., in preparation). In this clump the kinetic temperature is higher than in the rest of our sample, probably implying that depletion is less marked.

3. Observations and data reduction

The observations were made with APEX in July 2005 (RCrA and L183) and in October and November 2005 (OriB9). The 372421.364 MHz line of H_2D^+ was observed in the upper side band with the APEX-2A SIS DSB receiver. The HPBW of the telescope is about 17″ at this frequency. The observing mode was position switching with the off position −30′ away in RA. The integration time for each scan was 20 s. A calibration measurement was done every 10 min. The first observations (RCrA) were made with the ASC 2048 channel autocorrelator using a bandwith of 128 MHz. Because the performance of the system was unsatisfactory with the ASC, the MPIfR Fourier transform spectrometer, FFTS, was used for all subsequent observations. The 1 GHz bandwith of the FFTS was divided into 16384 channels resulting in a channel width of 61 kHz which corresponds to ~49 $\mathrm{m\,s^{-1}}$ at the observed frequency. The observing conditions ranged from excellent (PVW 0.2 mm, zenith opacity 0.24 at 372 GHz) to reasonable (PVW 0.7 mm, zenith opacity 0.6 at 372 GHz). Depending on the weather and the elevation of the source, the DSB system temperature was between 130 and 300 K.

Most of the observed spectra have ripple due to variations of sky emission, reflections in the telescope optics and instability of the receiver. In the data reduction the possible low frequency ripple was first fit with a sinusoidal baseline whereafter possible higher frequency ripple was removed by masking the corresponding frequency in the Fourier transform. Finally, a first order baseline was subtracted around the source velocity. The mirror sideband of the receiver, centred at about 360 GHz, lies at a more transparent frequency than the signal sideband. The difference in the atmospheric opacity between the side bands was estimated using an atmospheric model and was taken into account in the calibration at the telescope. The telescope time spent on this project is 19.5 h.

Table 1. Target positions.

Core	α_{2000} (h m s)	δ_{2000} (° ′ ″)	$T_{\rm kin}$ (K)
IRAS 05405-0117	05 43 02.5	–01 16 23	10
OriB9 E	05 43 05.2	–01 16 23	10
OriB9 N	05 43 07.8	–01 15 03	10
L183-N	15 54 08.8	–02 51 00	10*
L183-S	15 54 08.8	–02 52 38	7*
RCrA NW	19 01 47.7	–36 55 15	15–18

* $T_{\rm dust}$ derived from the 450/850 μm ratio (Kirk & Ward-Thompson 2006, private communication).

4. Results

The Hanning smoothed spectra are shown in Fig. 1. A summary of the observations with the line parameters from Gaussian fits is presented in Table 2.

The H_2D^+ line is detected towards L183-S and 20″ north and south of it. The line in L183-S (0, 0) with the best S/N is single peaked, but suggests slight asymmetry. The *FWHM* (0.42 $\mathrm{km\,s^{-1}}$) is a little larger than expected from thermal broadening at $T_{\rm kin}$ = 7 K (0.28 $\mathrm{km\,s^{-1}}$). Our L183 positions lie near positions included in the N-S oriented H_2D^+ strip observed at the Caltech Submillimeter Observatory (CSO) by Vastel et al. 2006. Their position $\Delta\delta = 0''$ corresponds to the offset $(-4'', +19'')$ from L183-S. The antenna temperatures measured at APEX towards L183-S $(0'', 0'')$ and $(0'', +20'')$, and the 3σ upper limit $T_A^* < 0.4$ K obtained towads L183-N (close to Vastel's $\Delta\delta = +80''$) are consistent with the CSO data. On the other hand, the line intensity at L183-S $(0'', -20'')$, $T_A^* \sim 0.9 \pm 0.2$ K, is surprisingly high in view of the fact that Vastel et al. obtain antenna temperatures of ≈0.7 K and 0.4 K towards the offsets $(-4'', -11'')$ and $(-4'', -31'')$ from L183-S, respectively. This suggests that the H_2D^+ distribution peaks slightly south of the dust emission peak but falls very steeply towards the southern end of the dense ridge.

In OriB9, weak H_2D^+ lines with $T_A^* \approx 0.12$ K at $\upsilon_{\rm LSR} \sim$ 9.1–9.2 $\mathrm{km\,s^{-1}}$ are detected towards the two starless condensations, OriB9 E and N. The LSR velocities agree with those of the previously observed NH_3 (9.2 $\mathrm{km\,s^{-1}}$ at OriB9 E and N) and N_2H^+ (9.2 $\mathrm{km\,s^{-1}}$ at the IRAS position) lines. An upper limit of 0.10 K (3σ) is obtained towards IRAS 05405-0117. This spectrum has, however, another line with $T_A^* \sim 0.4$ K at an about 250 MHz higher frequency. The most probable identification is $N_2H^+(4-3)$ at 372.67 GHz in the signal band (USB, $\upsilon_{\rm LSR}$ = 9.2 $\mathrm{km\,s^{-1}}$). We estimate from the $N_2H^+(1-0)$ data of Caselli & Myers (1994) that the N_2H^+ column density towards IRAS 05405-0117 is ~6–8 × 10^{12} $\mathrm{cm^{-2}}$. The intensity of the supposed $N_2H^+(4-3)$ line is consistent with this value. This line is not detected in other spectra.

Towards RCrA NW we obtained a 3σ upper limit of 0.3 K. The observations were made at low elevations. Furthermore, the system temperature was higher than expected from the observing conditions, probably because of problems with the integration of the ASC correlator into the system.

5. Column densities and abundances

The observed H_2D^+ line has quadrupole hyperfine structure due to the spins of D and the two H nuclei. The splitting is, however, very small ($\Delta\nu \sim 80$ kHz, Jensen et al. 1991) compared with the Doppler width at 10 K ($\Delta\nu \sim 420$ kHz), and we treat the line as if

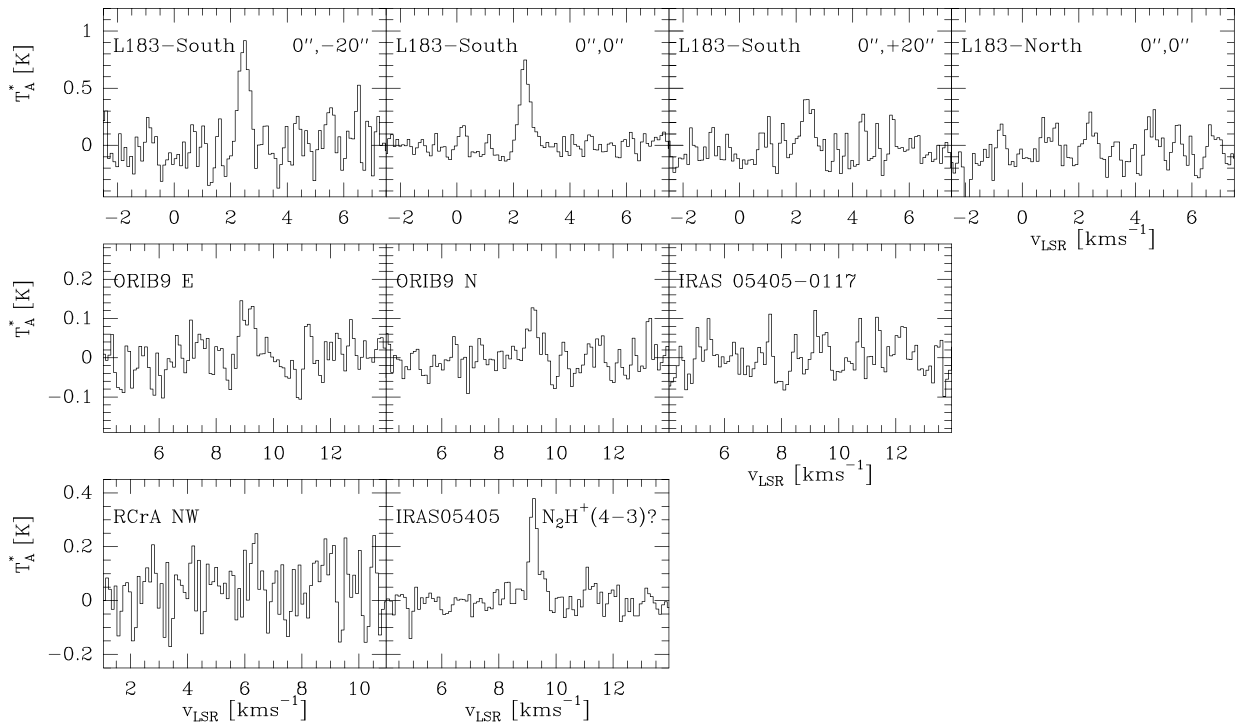

Fig. 1. The observed $H_2D^+(1_{10}–1_{11})$ spectra after Hanning smoothing (Δv = 98 m s^{-1}). *Top*: L183-S and L183-N. *Middle*: OriB9-E, OriB9-N and IRAS 05405-0117. *Bottom left*: R CrA NW (ASC spectrometer). *Bottom right*: the probable detection of $N_2H^+(4–3)$ at 372.67 GHz towards IRAS 05405-0117. The line can be seen in the same FFTS spectrum as the 372.42 GHz H_2D^+ line.

Table 2. Line parameters derived from Hanning smoothed spectra with a velocity resolution of 98 m s^{-1}.

Line/ position	T_A^* (K)	v_{LSR} (km s^{-1})	$\Delta v(FWHM)$ (km s^{-1})	rms (K)
H_2D^+ $(1_{10}–1_{11})$				
IRAS 05405-0117	–			0.03
OriB9 E	0.13	9.11 ± 0.06	0.56 ± 0.12	0.04
OriB9 N	0.11	9.20 ± 0.06	0.42 ± 0.15	0.03
L183-N	–			0.13
L183-S (0″, 0″)	0.68	2.42 ± 0.02	0.42 ± 0.04	0.05
L183-S (0″, −20″)	0.90	2.47 ± 0.03	0.41 ± 0.06	0.15
L183-S (0″, +20″)	0.42	2.41 ± 0.06	0.47 ± 0.13	0.10
RCrA NW	–			0.10
N_2H^+ $(4-3)$				
IRAS 05405-0117	0.37	9.22 ± 0.01	0.34 ± 0.04	0.04

it had a single component. We estimate the *ortho*-H_2D^+ column densities, $N(o-H_2D^+)$, in the same manner as done in Caselli et al. (2003). A lower limit for the excitation temperature, T_{ex}, is obtained from the observed T_A^* by assuming that the line is optically thick. The kinetic temperature of the gas, T_{kin}, sets an upper limit.

Towards L183-S (0, 0), the reasonable T_{ex} range is 6.3 K < T_{ex} < 10 K (allowing T_{kin} be slightly higher than the dust temperature). Assuming that $T_{ex} = T_{dust}$ = 7 K, and that the source fills the main beam uniformly, we arrive at the values $\tau_0 = 1.25$ and $N(o-H_2D^+) = 2.7 \times 10^{13}$ cm^{-2}. The main beam efficiency, η_{MB}, is assumed to be 0.7. This column density is very close to that found by Caselli et al. (2003) towards the centre of L1544. The peak H_2 column density towards L183-S derived from SCUBA data is 9.1×10^{22} cm^{-2} (Kirk & Ward-Thompson 2006, private communication). Using this value we obtain the fractional *ortho*-H_2D^+ abundance $X(o-H_2D^+) = 3 \times 10^{-10}$. By varying T_{ex} in the given range, $N(o-H_2D^+)$ and $X(o-H_2D^+)$ decrease (higher T_{ex}, smaller τ_0) or increase (lower T_{ex}, larger τ_0) by a factor of three. The line shape does not support, however, the idea of large opacities, and we think the values corresponding to T_{ex} = 7 K are the most likely.

OriB9 is little studied and dust continuum measurements are not available. The T_{kin} derived from ammonia is 10 K, and the minimum T_{ex} from the line intensity is 4 K. Using the assumption T_{ex} = 7 K, which is midway between the two extremes, we get $\tau_0 \sim 0.13$ and $N(o-H_2D^+) \sim 3.0 \times 10^{12}$ cm^{-2} towards N and E. The ammonia column density in these positions is $\sim 10^{15}$ cm^{-2}. Assuming that the fractional NH_3 abundance is 3×10^{-8} (e.g. Harju et al. 1993) we get $X(o-H_2D^+) \sim 1 \times 10^{-10}$. The line profiles with rather poor S/N ratios do not exclude large optical thicknesses. The column density range implied by the possible T_{ex} values is $\sim 1.0 \times 10^{12}$–5×10^{13} cm^{-2}, and the derived fractional abundance has the corresponding uncertainty.

According to the model of Walmsley et al. (2004), the characteristic steady-state value of the *o*/*p*-ratio of H_2D^+ is ~ 0.3 in the density range $n_{H_2} \sim 10^5$–10^6 cm^{-3} appropriate for the objects of this study. Adopting this *o*/*p*-ratio the total H_2D^+ abundances in L183-S and OriB9 become $\sim 1.3 \times 10^{-9}$ and $\sim 4 \times 10^{-10}$.

6. Discussion

The performance of APEX and its equipment, and the atmospheric transmission on Chajnantor are found to meet very high standards. The telescope is therefore likely to become a very important tool for studies of molecular cloud interiors and star formation using H_2D^+, and other "difficult" molecules.

The present observations towards a small sample of dense cores with some diversity of physical characteristics suggest that either an elevated temperature (as in R CrA NW) or the presence of an embedded star (as towards IRAS 05405-0117), even if there is little evidence for star-cloud interaction, decreases the changes to find H_2D^+. The kinetic temperature, velocity dispersion and the fractional H_2D^+ abundance in OriB9 are similar to those in the prestellar dark cloud cores L1544, 16293E, and L183, where strong emission of this line has been detected previously. The masses and the central densities of these nearby cores are 2−3 $M_\odot$ and $\sim 10^6$ cm^{-3}, respectively (Vastel et al. 2006, and references therein). The total mass of the OriB9 core estimated from ammonia is of the order of 100 $M_\odot$ (Harju et al. 1993), and the subcondensations seen in the N_2H^+ map (Caselli & Myers 1994) are likely to be an order of magnitude more massive than L1544, 16293E, or L183. A (sub)millimetre continuum map is needed to confirm this. Nevertheless, OriB9 seems to be capable of forming a massive star or a dense cluster of low- to intermediate-mass stars, and is therefore exceptional among sources detected in H_2D^+ so far.

This detection confirms the existence of very cold, quiescent, dense cores in massive star forming regions. The previous evidence for such objects is scarce. Some infrared dark clouds (IRDCs) have gas temperatures approaching 10 K and ammonia linewidths slightly below 1 km s^{-1} (Pillai et al. 2006). Yet another massive core with these characteristics has been recently found in the region of ISOSS J18364-0221 (Birkmann et al. 2006). The linewidths in these objects are, however, clearly larger than in OriB9. On the other hand, only a small fraction of IRDCs have been observed in spectral lines to date. Because compression leads to an intensified cooling by molecules and dust, the collapse of all dense cores should be preceded by a cold, quiescent phase. Very cold GMC cores may have remained indiscernible because of their short life-time or the fact that large-scale surveys are usually biased towards the presence of a certain molecular species which might be depleted in the coldest regions.

As discussed recently by Flower et al. (2006), the H_2D^+ abundance depends inversely on the *ortho*:*para* ratio of H_2, which is largest at early stages of core evolution. Consequently, a high degree of deuterium fractionation is a sign of matured chemistry characterized by a low *o*/*p* H_2 and probably a high degree of molecular depletion. The *ortho*-H_2D^+ detection towards OriB9 suggests an evolved chemical stage and tells of a longlasting prestellar phase. However, estimates of the *o*/*p* ratio of H_2 and the degree of deuterium fractionation using other tracers are needed to confirm this. Despite these obstacles, it seems viable to use the 372 GHz H_2D^+ line together with chemistry models to estimate timescales related to the early evolution of massive cores.

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