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DETECTION OF H_2D^+: MEASURING THE MIDPLANE DEGREE OF IONIZATION IN THE DISKS OF DM TAURI AND TW HYDRAE

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ABSTRACT

We report the first detection of the ground transition of the ortho-H_2D^+ molecule toward one disk source, DM Tau, a tentative detection toward TW Hya, and an upper limit toward LkCa 15. The three observed sources possess young gas-rich disks with large CO depletion factors. We argue that the observed ground ortho-H_2D^+ line originates in the outer disk midplane gas, which is cold and depleted of CO. Since H_2D^+ is likely the most abundant ion, the measured line intensity allows to estimate the ionization degree in the midplane gas of the outer disk. In DM Tau the electron abundance is 7×10^{-10}, in TW Hya it is about 4×10^{-10}, and in LkCa 15 it is less than about 2×10^{-9}. This implies that the ionization in the disks is large enough for the magnetorotational instability to operate. The required ionization rate, 5×10^{-17} s^{-1}, in TW Hya is consistent, within the associated uncertainty, with normal cosmic-ray irradiation, whereas in DM Tau it is a factor of 10 lower than the canonical value.

Subject headings: ISM: molecules — planetary systems: protoplanetary disks — stars: formation — stars: pre–main-sequence

1. INTRODUCTION

Circumstellar disks around young stars are expected to be the sites of planet formation. When and exactly how planets form depends on the evolution of the disks: the accretion properties, the dispersal of gas from the disk, and when and how dust coagulation proceeds. In this Letter we focus on the bulk of the disk mass, namely, on the disk midplane gas and, in particular, on its ionization degree, a key parameter for the viscous disk accretion.

It is a well-known problem that direct observations of the bulk of the disk gas are difficult to achieve. The main element, hydrogen, is present in H_2 molecules, but the rotational lines of H_2 only probe the warm ($\gtrsim$100 K) gas in the disk (Thi et al. 2001; Richter et al. 2002). The second most abundant molecule, CO (the favorite tracer of gas in molecular clouds), probes colder gas but unfortunately not the disk midplane gas. Indeed, the molecular distribution in disks is thought to occur in three main layers. Close to the surface of the disk, CO (and practically all other molecules except very stable ones, such as polycyclic aromatic hydrocarbons) will be dissociated by energetic radiation—UV and X-rays (Aikawa & Herbst 1999; Willacy & Langer 2000; van Zadelhoff et al. 2003). Close to the midplane, which is completely shielded from energetic radiation, practically all molecules, including CO, freeze out onto dust grains (Aikawa & Herbst 2001; Aikawa et al. 2002). CO, like most other molecules, is therefore confined to the transition region between these two layers, where the energetic radiation is attenuated enough to allow a population of molecules to exist, but where the temperatures are high enough to prevent freezing out. Recent studies have observationally and theoretically demonstrated that in very cold and CO-depleted gas, the deuteration degree of doubly and triply deuterated molecules is enhanced by up to 8 orders of magnitude (Ceccarelli et al. 1998; Ceccarelli 2002; Roberts & Millar 2000; Roberts et al. 2003). Indeed deuteration and depletion proceed in parallel: the larger the depletion, the larger the deuteration degree (Bacmann et al. 2003). Since H_2 has a very low binding energy, H_2 is practically the last neutral molecule expected to stay gaseous in the midplane disk (see § 3 for a detailed discussion of this point). As a consequence, the molecular ion formed by the H_2 ionization of cosmic rays, H_3^+, is also expected to be the most abundant ion. Unfortunately, H_3^+ is practically undetectable in cold gas. However, for the reason explained above, its deuterated form, H_2D^+, is expected to be abundant in the midplane disk. This expectation is strengthened by the H_2D^+ detection in a low-mass protostar (Stark et al. 1999) and a prestellar core (Caselli et al. 2003), where the gas is cold and CO depleted, similarly to the disk midplane gas. In the latter source the H_2D^+/H_3^+ ratio is about unity. For this reason, we searched for the ground transition of the ortho-H_2D^+, which promises to be a valuable probe of the midplane gas, capable of measuring the degree of ionization. In this Letter we report the detection of the ortho-H_2D^+ $1_{1,1}$–$1_{1,0}$ line toward DM Tau and TW Hya and an upper limit toward LkCa 15, all sources with young gas-rich disks.

Source backgrounds are as follows:

DM Tau.—DM Tau is a T Tauri star at 140 pc from the Sun, at the edge of the L1551 cloud. An extended disk of molecular gas was first discovered by Guilloteau & Dutrey (1994). Subsequently, Dutrey et al. (1997) carried out a survey of different molecules. The dust disk mass is 2×10^{-4} $M_\odot$, and the age is estimated to be around 5 Myr. The disk has a diameter of 12″ (=800 AU in radius). The CO depletion is estimated to be between 10 and 100, depending on the adopted model (Dutrey et al. 1997; Thi et al. 2001; Dartois et al. 2003).

TW Hya.—TW Hya is a T Tauri star located in the star-forming region nearest to the Sun, i.e., at 56 pc. Its age is estimated to be around 8 Myr (Webb et al. 1999). The disk has a diameter of 7″ (=200 AU in radius) and a dust mass of $\sim 1.5 \times 10^{-4}$ $M_\odot$ (Wilner et al. 2000). If the dust-to-gas ratio is the standard one, the measured CO depletion is around 1500 (van Zadelhoff et al. 2001).

LkCa 15.—LkCa 15 is a T Tauri star at 140 pc from the Sun, in an outer region of the Taurus complex. Its age is estimated around 3–5 Myr (Simon et al. 2000). The surrounding

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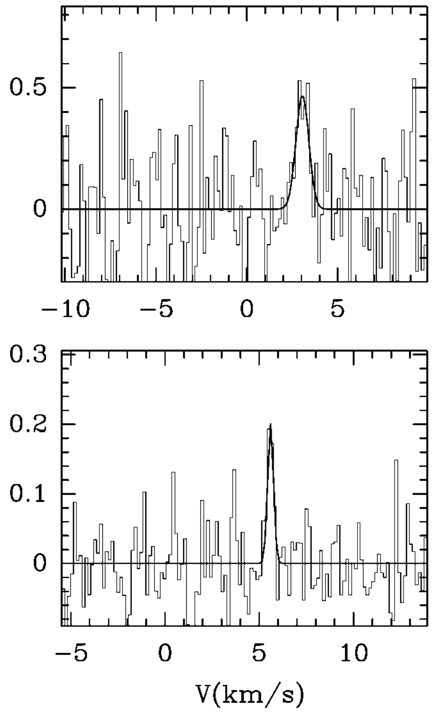

FIG. 1.—Observed H_2D^+ spectrum toward TW Hya (*top*) and DM Tau (*bottom*). Units are T_{mb} in K. The lines peak at 3.0 and 5.5 km s^{-1} in TW Hya and DM Tau, respectively, consistent with previous observations of v_{LSR} in DM Tau (Dutrey et al. 1997) and TW Hya (van Dishoeck et al. 2003)

disk has a diameter of 6″ (=435 AU in radius) and a dust mass of $2 \times 10^{-4}\ M_\odot$ or larger (Duvert et al. 2000; Chiang et al. 2001). Molecular emission has been observed by Qi et al. (2003) and Thi et al. (2001). If the dust-to-gas ratio is the standard one, the measured CO depletion amounts to around 5–300, depending on the adopted model.

2. OBSERVATIONS AND RESULTS

The observations of the ortho-H_2D^+ $1_{1,1}$–$1_{1,0}$ line (at 372.42134 GHz) were carried out 2003 December 17–19 at the Caltech Submillimeter Observatory (CSO).[5] The receiver was tuned (double sideband) at the frequency of 372.421340 GHz. The beam size is 22″ at this frequency, and the beam efficiency is 74%.[6] The system temperatures were ∼1500 and 3500 K during the observations of DM Tau and TW Hya, respectively. Atmospheric calibration scans were performed every 30 minutes on average. Pointing was checked every 2 hr and found stable within a few arcseconds. The spectra were obtained in the wobbler switching mode, with a chop throw of 180″. The obtained rms is 50 and 160 mK on the 0.15 km s^{-1} velocity bin in DM Tau and TW Hya, respectively. Given the high sensitivity of these observations to the water vapor, the calibration uncertainty is about 30%.

Results of the observations are shown in Figure 1 and reported in Table 1. The line flux is detected with a 4.7 σ confidence level in DM Tau and 3.2 σ in TW Hya (we therefore consider the latter a tentative detection), while the line is undetected in LkCa 15.

A search carried out at the James Clerk Maxwell Telescope gives 2 σ upper limits of about 0.3 K km s^{-1} in TW Hya (W.-F. Thi & E. F. van Dishoeck 2004, private communication), apparently in contrast with the CSO detection. The H_2D^+ line widths are narrow, ∼0.5 km s^{-1}, similar to what is observed in TW Hya in the DCO^+ (van Dishoeck et al. 2003). In DM Tau the H_2D^+ line is slightly narrower than the HCO^+ 1–0 line, but we note that the latter is narrower than the HCO^+ 3–2 line (Dutrey et al. 1997).

The ortho-H_2D^+ column density (Table 1) has been computed assuming that the gas temperature is 10 K, the line is LTE populated, and it is optically thin. The last two conditions are likely to be correct, for the ortho-H_2D^+ $1_{1,1}$–$1_{1,0}$ line critical density is about 10^6 cm^{-3} (Caselli et al. 2003), and the observed signals are very low, which implies relatively low H_2D^+ column densities (confirmed a posteriori). The gas temperature may be slightly larger, up to approximatively 15 K (Dullemond et al. 2002), depending on the geometry and adopted model. Increasing the temperature to 15 K would require a column density decreased by about 40%. Finally, using the H_2 column densities of Table 1 (derived from the observed dust mass and the disk sizes and assuming the canonical gas-to-dust ratio of 100), we derived the abundances reported in the same table. The total H_2D^+ abundance should be twice the ortho-H_2D^+ abundance, for the ortho-to-para H_2D^+ ratio is thought to be close to unity at 10 K (Pagani et al. 1992; Gerlich et al. 2002), although this depends on the (unknown) ortho-to-para ratio of H_2 (Walmsley et al. 2004).

3. DISCUSSION

H_2D^+ is formed via the reaction $H_3^+ + HD \rightarrow H_2D^+ + H_2$. Because the inverse reaction is endothermic with a barrier of ∼250 K, in cold gas the H_2D^+/H_3^+ ratio is greatly enhanced with respect to the elemental D/H ratio. Generally, H_2D^+ is destroyed by reactions with CO and, to lesser extent, heavy molecules/atoms and direct recombinations with electrons and negatively charged grains. Hence, in cold and CO-depleted gas and when charged grains are negligible (see below), the H_2D^+/H_3^+ ratio can be easily estimated, and it is given by (e.g., Caselli et al. 2003, where we corrected for the different adopted temperature, 10 K here)

$$\frac{x(H_2D^+)}{x(H_3^+)} = 7\,\frac{k_f}{3.5 \times 10^{-10}}\left[\frac{228}{f_{dep}} + 3.6 \times 10^8 x(e^-)\right]^{-1}, \quad (1)$$

where k_f is the H_2D^+ formation rate equal to 3.5×10^{-10} (Gerlich et al. 2002). Here f_{dep} is the CO depletion factor, defined as the inverse of the CO abundance divided by the canonical value

[5] The CSO is funded by the NSF through contract AST 99-80846.

[6] See http://www.submm.caltech.edu/cso.

TABLE 1
PARAMETERS OF THE THREE OBSERVED SOURCES

Source	$N(H_2)$ (cm^{-2})	CO Depletion	$T_{mb}\Delta v$[a] (K km s^{-1})	$N(o\text{-}H_2D^+)$ (10^{13} cm^{-2})	$x(o\text{-}H_2D^+)$ (10^{-10})	$x(e^-)$ (10^{-10})	ζ (10^{-17} s^{-1})
DM Tau	2.7×10^{22}	∼10–100	0.076 ± 0.016	0.44 ± 0.09	1.7 ± 0.4	7.0	0.1
TW Hya	3.2×10^{23}	∼1500	0.390 ± 0.120	6.4 ± 2.1	2.1 ± 0.7	4.0	5
LkCa 15	1.6×10^{23}	∼300	≤0.45	≤10	≤6	<20	≤20

[a] Observed $T_{mb}\Delta v$ in DM Tau and TW Hya and upper limit toward LkCa 15. The upper limit is 2 σ and has been computed by assuming a line width similar to that observed in CO, namely, 3 km s^{-1}.

10^{-4} (Frerking et al. 1982). Equation (1) assumes that all the molecules and atoms freeze onto grain with at least the same efficiency as CO, so that CO is the main molecule/atom H_2D^+ destroyer. This may not be entirely true for atomic oxygen, which is only a factor of 4 less efficient than CO to destroy H_2D^+. The atomic oxygen abundance could indeed be large (Caux et al. 1999; Vastel et al. 2000), but it is debatable whether O remains gaseous in the disk midplane, where it is believed to efficiently form water ice. N_2 is expected to freeze out onto grains at slightly lower temperatures than CO, so it may be present in regions with depleted CO (Qi et al. 2003), but at densities larger than about 10^6 cm^{-3}, as in the case of the midplan gas, also N_2 freezes out onto the grains (Aikawa et al. 2002; Caselli et al. 2003). We conclude, therefore, that the N_2 abundance is likely negligible and equation (1) applicable. Note that even taking into account this additional destruction term in equation (1) would not change the results by more than a factor of 2 at most, considering $x(N_2) = 2 \times 10^{-5}$ (Qi et al. 2003).

In general, the most abundant molecular ions in undepleted cold gas are HCO^+, H_3O^+, and H_3^+ (Lee et al. 1996). In the case of severe depletion of CO and H_2O, the positive charge is likely carried by H_3^+ and its isotopes, especially when also N_2 freezes out onto the grains (Roberts et al. 2003). It is possible that metal atoms carry some of the positive charge, but they are likely fully depleted in the cold midplane, so they should not be a source of a large uncertainty. The negative charge can be carried by small dust grains if those are abundant, but in the disk midplane small grains will coagulate into bigger grains and therefore be severely depleted as well. In this case, the negative charge will be dominated by free electrons, and charge conservation requires that the $H_3^+ + H_2D^+$ abundance[7] is equal to the electron abundance. Thus, it holds

$$x(\mathrm{H_2D^+}) = 7\,\frac{k_f}{3.5\times10^{-10}}\,x(e^-)\left[7\,\frac{k_f}{3.5\times10^{-10}} + \frac{228}{f_{\mathrm{dep}}} + 3.6\times10^{8}x(e^-)\right]^{-1}. \qquad (2)$$

Equation (2) gives the H_2D^+ abundance $x(H_2D^+)$ as function of the electron abundance $x(e^-)$. Thus, the H_2D^+ abundance measures the degree of ionization of the midplane gas. Figure 2 shows $x(H_2D^+)$ versus $x(e^-)$, together with the observed values in DM Tau and TW Hya. From the curve, we find an electron abundance in the midplane of the TW Hya and DM Tau disks about equal to $\sim 4 \times 10^{-10}$ and $\sim 7 \times 10^{-10}$, respectively, and an upper limit of $\sim 2 \times 10^{-9}$ in LkCa 15. Note that in TW Hya and DM Tau, the estimated CO depletion factor is larger than 1000 and around 100, respectively (§ 2), so that equation (2) should be fully applicable and the estimate of the ionization degree reliable. For a validation of the method, in Figure 2 we also report the values observed in L1544 (derived independently from other ions than H_2D^+): $x(H_2D^+) \sim 10^{-9}$ (Caselli et al. 2003) and $x(e^-) = 2 \times 10^{-9}$ (Caselli et al. 2002b). Note that the effective CO depletion in the center of L1544 is much larger than 10, as predicted by Caselli et al. (2002a), and as indeed the figure suggests. Very likely the largest uncertainty in the determination of the ionization degree from the present H_2D^+ observations lies in the underlying assumption that H_3^+ and H_2D^+ are the most abundant ions. Recent chemical models would suggest that it is possible that H^+ and D_3^+ (Walmsley, Flower, & Pineau des Forets 2004) or N_2D^+ (Roberts et al. 2003) have abundances comparable to H_3^+ and H_2D^+. However, H^+ is expected to recombine very efficiently with charged grains, and a large H^+ abundance in the disk midplane is unlikely (see, e.g., Walmsley et al. 2004). In DM Tau, Dutrey et al. (1997) obtained an upper limit to the N_2H^+ abundance of $\sim 2 \times 10^{-10}$, i.e., 1.5 times lower than the observed H_2D^+. In the most extreme case, the Roberts et al. (2003) model predicts $N_2D^+/N_2H^+ \sim 1$, so that at least in the case of DM Tau, $H_2D^+ + H_3^+$ seem to be most the abundant ions. For completeness, in DM Tau the HCO^+ abundance, $\sim 5 \times 10^{-10}$ (Dutrey et al. 1997), is at most slightly larger than the H_2D^+ abundance, but very likely the observed HCO^+ emission originates in the warm layer rather than on the disk midplane, and the larger ionization can be caused by the penetration of X-rays (Igea & Glassgold 1999). In TW Hya the HCO^+ abundance has been estimated to be 5×10^{-11} (Wilner et al. 2003), much lower than the H_2D^+ abundance, whereas no detection of N_2H^+ exists with a limit of 2×10^{-11} (Thi et al. 2004). Thus, the reported estimate of the midplane ionization degree seems reliable. However, to check how missing an ion carrier would impact the estimate of the ionization degree from the H_2D^+ observations, we reported in Figure 2 a curve computed assuming that only half of the charge is carried by H_3^+ and H_2D^+. For the same H_2D^+ abundance, the estimated ionization degree would be half as large. An additional source of uncertainty is the gas-to-dust ratio, implicitly used to derive the abundances from the dust continuum observations.

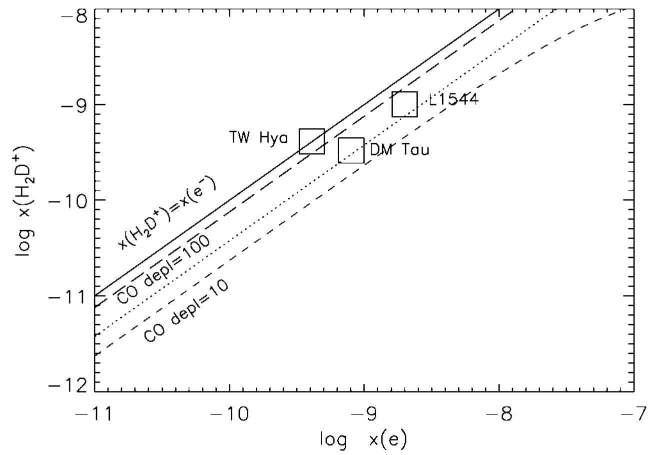

Fig. 2.—Theoretical H_2D^+ abundance as function of the electron abundance and parameterized by the CO depletion factor: 100 (*long-dashed line*) and 10 (*short-dashed line*). The dotted line is computed for CO depletion equal to 100 and assuming that half of the positive charge is carried by other ions than $H_2D^+ + H_3^+$. The squares mark the observed H_2D^+ abundance in TW Hya and DM Tau on the relevant CO depletion curves: the CO depletion factor is taken from the literature (§ 2) and given by Table 1. The square labeled L1544 shows the H_2D^+ and electron abundances, as measured by Caselli et al. (2002b, 2003).

Even within this relatively large uncertainty, the estimate of ionization degree on the midplane disk is important, for the degree of ionization is an important parameter for the viscous evolution of the disk. Currently, the most promising mechanism that can act as a source for viscous dissipation in the disk leading to the inward motion of matter and the corresponding outward motion of angular momentum is the magnetorotational instability (Balbus & Hawley 1998). For this instability to work,

[7] Recent theoretical modeling predicts also abundant HD_2^+ and D_3^+ (Roberts et al. 2003), but observations toward L1544 seem to contradict these predictions (C. Vastel 2004, unpublished). We therefore just consider the first isotopomer of H_3^+ in our analysis.

the disk matter must have a minimum degree of ionization that is given by (Gammie 1996)

$$x_{BH} \approx 1.4 \times 10^{-14} \alpha^{-1/2} \left(\frac{r}{1\ \mathrm{AU}}\right)^{-3/2} \frac{500\ \mathrm{K}}{T} \left(\frac{M_*}{M_\odot}\right)^{1/2}, \quad (3)$$

where α is the usual disk viscosity parameter, r the distance from the star, T the gas temperature, and M_* the stellar mass. Using a distance of 100 AU, a temperature of 10 K, and $\alpha \approx 0.01$ for a solar-like star (Brandenburg et al. 1996), $x_{BH} \approx 7 \times 10^{-15}$. Therefore, in the outer disk regions of both DM Tau and TM Hya, the measured ionization is clearly large enough to support viscous accretion through the magnetorotational instability. The main sources of ionization in disks are UV radiation (which is active at the disk surface only), X-rays (which penetrate effectively down to a column of approximately 10 g cm^{-2}; Igea & Glassgold 1999), and cosmic rays (which reach down to 100 g cm^{-2}). There is, however, considerable uncertainty about the cosmic-ray fluxes in the disk environment since the strong magnetic fields and winds associated with young stars may be able to create a cosmic-ray poor zone. The present observations allow to estimate the cosmic-ray ionization rate in the disk midplane, assuming a canonical gas-to-dust ratio and the relation between the density and the ionization rate ζ, $x(e^-) = (\zeta/\beta n_0)^{1/2}$. Using the pressure scale height, H_p, we can convert the H_2 column density N_{H_2} into a midplane density: $n_0 = N_{H_2}/(2\pi H_p^2)^{1/2}$. Assuming a typical distance of the emission from the star of $\frac{2}{3}$ for the measured disk size and a midplane temperature of 10 K, we can compute the midplane density. Then, assuming that no metal atoms exist in the gas phase and that small dust grains have in the midplane been efficiently depleted by coagulation, the main recombination route is dissociative recombinations with a rate coefficient $\beta = 4 \times 10^{-7}$ cm^3 s^{-1} (at $T = 10$ K; McCall et al. 2003). The derived ionization rates in the three disks are given in Table 1. The ionization rate found in TW Hya is 5×10^{-17} s^{-1}, in rough agreement with the canonical value $\sim 3 \times 10^{-17}$ s^{-1} (e.g., Webber et al. 1998), whereas it is relatively low, 1×10^{-18} s^{-1}, in DM Tau. In the protostellar cores L1544 and L1517B, the ionization rate is also low, around 6×10^{-18} s^{-1} (Caselli et al. 2002b and Tafalla et al. 1998, respectively), a fact that has been interpreted as evidence of shielding of cosmic rays in the interior of the cores. However, since the column densities in the outer disk regions of DM Tau are only of the order of 1 g cm^{-2}, shielding of the disk interior cannot cause the observed reduction in DM Tau. The lower ionization rate may therefore reflect a lower local intensity of the cosmic-ray irradiation or a substantially different gas-to-dust ratio. Observations toward other disk sources close to DM Tau, where the cosmic-ray ionization rate is similar, may distinguish between these two possibilities.

To conclude, H_2D^+ observations can be used to derive the degree of ionization of the gas in the disk midplane, where the bulk of the disk mass resides. The current measurements probe the outer disk. In the inner disk regions, where much larger column densities lead to effective shielding of the disk midplane, the resulting low degree of ionization can lead to the formation of dead zones that are decoupled from accretion (Gammie 1996). Future observations with the Atacama Large Millimeter Array will be able to resolve the inner regions of disks and may use measurements of H_2D^+ to study this phenomenon. Finally, measuring the cosmic ionization rate, as described above, in more sources belonging to the same complex can lead to measurement of the gas-to-dust ratio and its evolution in the examinated sample.

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