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FUSE Observations of Molecular Hydrogen in PMS Stars

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Abstract. Pre-main sequence stars exhibit rich molecular hydrogen emission and absorption spectra in the FUV. We survey four PMS stars that have been observed with FUSE: the Classical T Tauri Stars TW Hya and V4046 Sgr, and the Herbig Ae/Be stars AB Aur and DX Cha. The spectrum of TW Hya and V4046 Sgr show H_2 fluorescence in Lyman (B-X) and Werner (C-X) bands caused by photoexcitation by Lyα, H_2 absorption occurs against line and continuum emission in the spectrum of AB Aur and DX Cha. We measure column densities of $\log(N_{H_2})$=20.2 ± 0.2 cm^{-2} towards AB Aur and $\log(N_{H_2}) = 19.4 \pm 0.2$ cm^{-2} towards DX Cha. The rotational excitation temperature of the H_2 gas around DX Cha varies from 300–500 K for different rotational levels, compared with 65–450 K the gas around AB Aur. We discuss the circumstellar origin of H_2 emission and absorption.

1. Introduction

Most previous studies of disks around PMS stars have relied upon the spectral energy distribution of micron-sized dust in the mm to IR wavelengths. Disk properties may then be inferred assuming a gas/dust ratio. Gas tracers such as CO may not accurately probe the gas because CO condenses into grains and dissociates easily. Recent studies of H_2 in the IR and UV have demonstrated that one can directly measure properties of the circumstellar gas without using dust or CO as a tracer.

Electronic transitions of H_2 occur in emission and absorption in the FUV. Analysis of HST/STIS observations of TW Hya by Herczeg et al. (2001) show that Lyman-band H_2 fluorescence is caused by photoexcitation from Lyα and probably originates in a circumstellar disk. Other CTTSs, such as T Tau, show extended H_2 emission reaching $20''$ from the star (van Langevelde et al. 1994). This extended H_2 may be shock-heated emission from the interaction of a stellar or disk wind with surrounding cloud material (Bally, Lada, & Lane 1993). FUSE spectra provide powerful diagnostics of ISM conditions because H_2 transitions from low energy levels occur primarily in the FUSE spectral region. Roberge et al. (2001) analyzed the FUSE spectrum of AB Aur and attributed the H_2 absorption to the interstellar medium. We present observations of H_2 emission

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Table 1: FUSE observations of PMS stars

Star	DX Cha	AB Aur	TW Hya	V4046 Sgr
HD	104237	31293	-	319139
Class	HAeBe	HAeBe	CTTS	CTTS
Spec. Type	A7	A0Ve	K7V	K5V
Distance (pc)	116	144	56	> 50
Age (Myr)	2	4±1	10	-
V	6.6	7.1	10.9	9.7
E(B-V)	0.15	0.19	0.0	0.30
Inclination	-	$< 45^o$	10 ± 5^o	37^o
Obs. Date	4/15/00	4/4/00	6/3/00	5/18/00
Exp. Time (s)	10587	13659	2081	15650
Aper.	30"×30"	30"×30"	30"×30"	30"×30"

and absorption around PMS stars that instead probe circumstellar environments.

2. Observations & Data Reduction

We observed TW Hya with FUSE and obtained spectra of one other CTTS and two Herbig Ae/Be stars from the FUSE archive (see Table 1). We processed the FUSE observations using version 1.8 of the standard CALFUSE pipeline. The observations shown in Fig. 1 are primarily from the LiF1a and LiF2a channels of the FUSE instrument. We binned the data into three pixel elements, smaller than the $R \approx 15,000$ spectral resolution of FUSE. We calibrated wavelengths using H_2 absorption lines, interstellar absorption lines and comparison with HST/STIS E140M spectra. The wavelength calibration of the LiF1a segment (990–1080 Å) for TW Hya and V4046 Sgr is uncertain.

The FUSE spectra of AB Aur and DX Cha have many strong emission and absorption features, including a rich spectrum of Fe II emission lines identified by Harper et al. (2001). Sallmen et al. (2000) presented the FUSE spectrum of V4046 Sgr, highlighting the strong O VI emission produced in an accretion shock near the star.

3. H_2 in Emission

Fluorescent Lyman-band H_2 emission in the UV arises from photoexcitation by Lyα 1215.67 Å. In the FUSE spectrum of the CTTS TW Hya and V4046 Sgr we identify the Lyman-band H_2 lines 1-1 R(3) at 1148.751 Å and 1-1 P(5) at 1161.864 Å and the Werner-band H_2 lines 0-2 Q(10) at 1127.160 Å and 0-3 Q(10) at 1172.031 Å. Table 2 shows the fluxes and pumping mechanism for these lines. The excited levels are pumped by the red wing of Lyα, which has strong emission from an accretion column. The Lyman-band lines are pumped from a lower level with energy $E'' = 1.2$ eV, and the Werner-band lines are pumped from a lower level with energy $E'' = 2.5$ eV. Although the latter energy is quite high, given the excitation mechanisms present in circumstellar material this level may be populated. Werner-band H_2 emission has only been observed previously in the FUSE spectrum of T Tau (Harper et al., 2001). Table 2 lists the fluxes of these lines.

Table 2: H_2 fluxes

Star	ID	$\lambda_{\rm obs}$ (Å)	Flux[1]	σ(Flux)[1]	Pump	$\lambda_{\rm Pump}$ (Å)
TW Hya	1-1 R(3)	1148.796	5.1	1.4	1-2 P(5)	1216.070
TW Hya	1-1 P(5)	1161.949	9.0	2.2	1-2 P(5)	1216.070
TW Hya	0-2 Q(10)	1127.346	10.7	1.1	0-4 Q(10)	1217.263
TW Hya	0-3 Q(10)	1172.177	17.2	2.4	0-4 Q(10)	1217.263
V4046 Sgr	1-1 R(3)	1148.758	2.8	0.5	1-2 P(5)	1216.070
V4046 Sgr	1-1 P(5)	1161.947	6.8	0.7	1-2 P(5)	1216.070
V4046 Sgr	0-2 Q(10)	1127.267	4.8	0.7	0-4 Q(10)	1217.263
V4046 Sgr	0-3 Q(10)	1172.041	9.0	0.8	0-4 Q(10)	1217.263

[1] 10^{-15} erg cm^{-2} s^{-1}

The Lyman-band lines are pumped from a lower level with energy $E'' = 1.2$ eV, and the Werner-band lines are pumped from $E'' = 2.5$ eV. Although the latter energy is quite high, given the excitation mechanisms present in circumstellar material this level may be populated. These pumps occur on the red wing of Lyα, which has strong emission from the accretion column.

Herczeg et al. (2001) predicted emission in the two Lyman-band lines based on HST/STIS E140M observations of TW Hya from 1160–1700 Å. However, the flux observed with FUSE is about 10 times fainter than predicted for optically thin emission. This difference suggests either a decrease in activity between the HST and FUSE observations or a wavelength-dependent extinction of the H_2 emission. The latter explanation is unlikely, as Rucinski & Krautter (1983) claim $E(B-V) \sim 0$ for TW Hya. Alternatively, the H_2 may be optically thick, reducing the emission we observe in transitions to low excitation states. Because the transition energy increases as the energy of the lower state decreases, the thickness of the lines would systematically occur at short wavelengths. This effect has been observed in the H_2 fluorescence in Mira (Wood et al. 2002).

4. H_2 in Absorption

In FUSE spectra of the Herbig Ae/Be stars AB Aur and DX Cha, we identify Lyman-band H_2 from the $J_l = 0$ to $J_l = 5$ levels in the ground vibrational and electronic state. These features are seen against emission lines, such as the O VI 1035 Ådoublet, C III 977 Å and Fe III 1064 Å, and against the continuum.

We fitted the H_2 absorption lines observed in the spectrum of DX Cha and AB Aur. The absorption lines are too narrow to be resolved by FUSE, and the poor S/N in the continuum prevents the measurement of weak absorption lines. Consequently, we could not simultaneously solve for both the column density in a given rotational level, $N(J)$, and the Doppler parameter b. However, if we assume that the non-thermal velocities contributing to b are less than 4 km s^{-1}, the column density does not depend on b. This effect occurs because for small b the instrumental profile dominates the fit to the width of the absorption line, so $N(J)$ does not change significantly in this region.

Figure 2 shows fits to selected spectral regions, assuming small b. We select the best-fit unblended lines to determine column densities for each level assuming

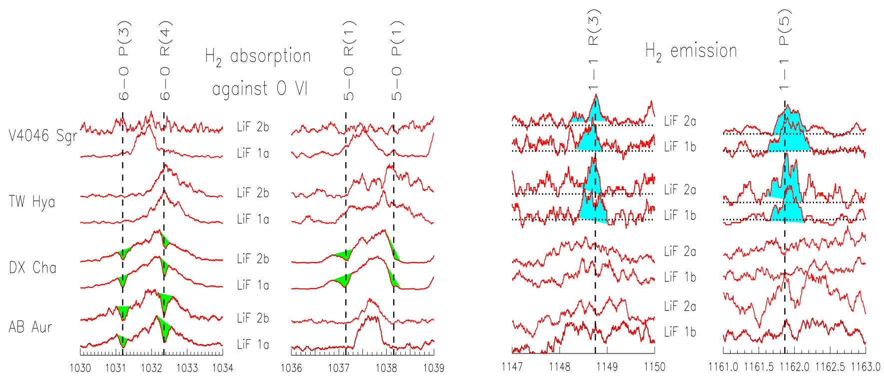

Figure 1. H_2 lines are seen in absorption around the Herbig Ae/Be stars (left) and in emission around the CTTS (right). Any weak H_2 emission from AB Aur and DX Cha at 1145 Å and 1161 Å would be masked by strong emission and absorption features.

$b = 2$ km s^{-1} (Table 3). We do not simultaneously fit many absorption lines from the same lower level because the S/N in some spectral regions is poor. Table 3 lists absorption lines used for each rotational level and the column density calculated for that line. We compare these results to other absorption lines from the same rotation level to ensure that different lines do not give significantly different results.

5. Origin of H_2

FUV H_2 emission may originate in either an outflow or a disk around a TTS. Herczeg et al. (2001) showed that H_2 emission lines in the HST/STIS E140M spectrum of TW Hya have a radial velocity, width and spatial extent consistent with disk emission. We do not expect to observe H_2 absorption in TW Hya and V4046 Sgr because their disks are viewed nearly face-on.

Table 3: H_2 column densities

	DX Cha			AB Aur		
J	ID	λ	log $N(J)$[1]	ID	λ (Å)	log $N(J)$[1]
0	4-0 R(0)	1049.364	18.0 (0.2)	0-0 P(0)	1108.127	19.93 (0.08)
1	0-0 P(1)	1110.062	19.2 (0.1)	0-0 R(1)	1108.633	19.7 (0.1)
2	0-0 P(2)	1053.281	18.4 (0.2)	3-0 P(2)	1066.897	18.6 (0.2)
3	6-0 P(3)	1031.190	18.41 (0.05)	6-0 P(3)	1031.190	18.7 (0.1)
4	6-0 R(4)	1032.347	17.76 (0.06)	3-0 P(4)	1074.310	18.2 (0.2)
5	4-0 R(5)	1061.694	17.0 (0.7)	-	-	-
$N(H_2)$	19.4 ± 0.2 cm^{-2}			20.2 ± 0.2 cm^{-2}		

Roberge et al. (2001) AB Aur: log $N(H_2)$=19.83±0.03, $T_{01} = 65$ K

[1]Error in column density shown in parentheses.

H_2 absorption may occur in the ISM or in circumstellar material. Roberge et al. (2001) argued that the absorption observed in the FUSE spectrum of AB

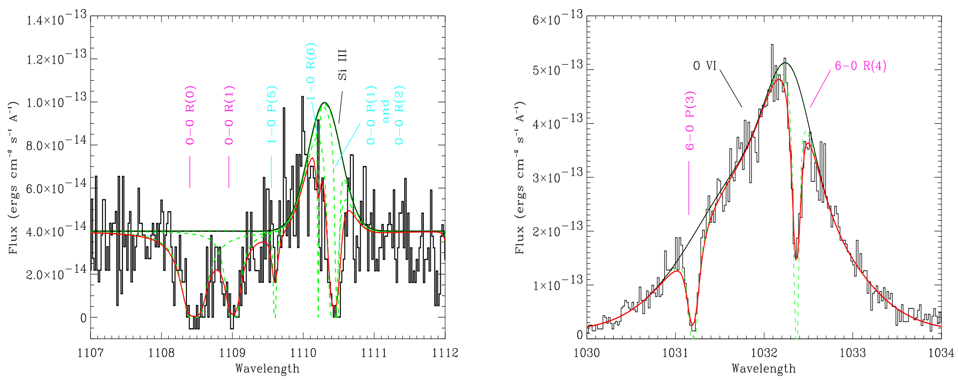

Figure 2. Fits to H_2 absorption profiles in AB Aur (left) and DX Cha (right), using $b = 2$ km s^{-1} (corresponding to $T = 500$ K for pure thermal broadening). The lines with magenta labels were used to determine column densities for the lower levels, while the blue labels represent lower levels whose column densities we measured with different transitions. The dashed green lines show the absorption profile prior to convolution with the instrumental profile. The red lines show our final fit to the data.

Aur is interstellar because AB Aur is closer to face-on than edge-on. However, the absorption may occur in a circumstellar envelope or in an outflow region rather than in a disk. Gry et al. (2001) measured excitation temperatures towards three B stars between 170 pc and 390 pc in the diffuse ISM. They found that the excitation temperature from the $N(J = 0)/N(J = 1)$ ratio is about 65 K. The excitation temperature for higher rotational levels, up to $J = 5$, is between 75 and 110 K. We calculate that the rotational excitation temperature in the circumstellar disk of H_2 around DX Cha is over 300 K (Fig. 3). The rotational temperature for $N(J = 0)/N(J = 1)$ around AB Aur is 65 K, but the temperatures of $J = 2$ to $J = 4$ correspond with 200-400 K (Fig. 3). The degree of excitation in the higher rotational levels is not consistent with ISM absorption. Moreover, models of IR and mm dust emission from DX Cha and AB Aur have indicated that most extinction towards these stars is circumstellar rather than interstellar (Voshchinnikov et al. 1996; Pezzuto et al. 1997). Consequently, we conclude that the H_2 absorption around DX Cha and AB Aur most likely originates in circumstellar material.

6. Discussion & Future Prospects

FUSE and HST/STIS observations of H_2 around PMS stars complement each other well. The FUSE bandpass provides a rich spectrum of H_2 absorption, while in the HST/STIS E140M bandpass hundreds of H_2 emission lines are accessible. Observations of H_2 absorption provide information on the populations of low energy levels of the ground electronic state. Fluorescent emission is primarily produced by photoexcitation from highly excited levels (1.0–3.8 eV) of the

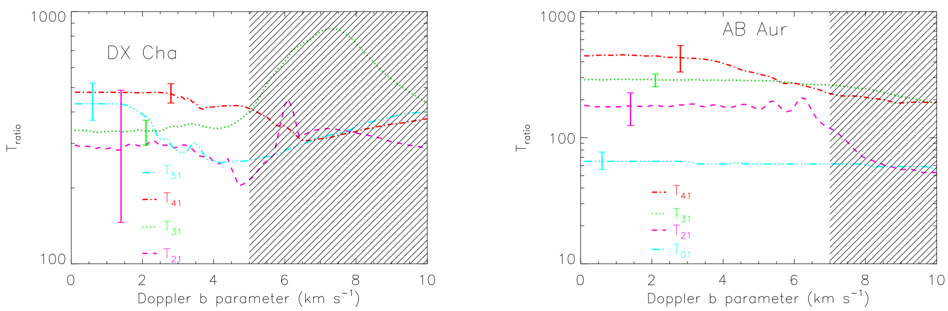

Figure 3. The rotational temperatures for the H_2 gas that correspond to the ratios $N(J)/N(J=1)$, versus the Doppler b paramter. The error bars shown apply to the unshaded region on the left. The shaded region indicates b values where the column density is poorly constrained, leading to large errors in the derived $N(J)$.

ground electronic state. Disk models predict energies of about 1000 K at 1 AU on the edge of the disk. However, Herczeg et al. (2001) show that the observed fluorescence is consistent with a temperature of about 3500 K. The excited H_2 may be explained by X-ray excitation from the protostar or shock-excitation.

Additional FUSE data exists for DX Cha and will be included in future analysis. We will also obtain a deep re-observation TW Hya to observe other H_2 emission lines and obtain an accurate upper limit of $N(H_2)$.

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