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Highly Excited UV H_2 emission around TW Hya

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Abstract. We observed the classical T Tauri star TW Hya with HST/STIS using the E140M grating. Fluorescent H_2 emission, consisting of 129 Lyman B-X lines from 19 upper rovibrational levels, dominates the spectral region from 1200–1650 Å. The H_2 is photoexcited to the B electronic state primarily by the broad stellar Lyα line, although the C II 1335 Å doublet, C III 1175 Å multiplet, and C IV 1550 Å multiplet also pump certain levels of H_2. From the observed H_2 fluorescence and the pumping flux of Lyα, we calculate the population of H_2 in the ground electronic state in the optically thin limit assuming steady-state equilibrium. We show that the excitation of H_2 in the ground electronic state is not thermal and consider different excitation mechanisms to explain the calculated distribution.

1. Introduction

The presence of disks around classical TTS (CTTS) is now well established observationally. Molecular hydrogen (H_2) is expected to be $\sim 10^4$ times more abundant than other gas tracers such as CO in the disks surrounding young stars. Since H_2 can survive up to temperatures of 4000 K, it is a good diagnostic for the gas in the disk. Molecular hydrogen around a CTTS was first detected using the 1-0 S(1) line in the IR spectrum of T Tau (Beckwith et al. 1978). Brown et al. (1981) discovered ultraviolet emission lines of H_2 in an IUE spectrum of T Tau. The origin of H_2 emission from CTTS is very important. Recent ground based images of T Tau shows the IR emission to be quite extended, reaching to $20''$ away (van Langevelde et al. 1994). The extended IR H_2 emission seen around T Tau and other young embedded sources like L1448 (Bally, Lada, & Lane 1993) is often interpreted as shock heated emission from the interaction of the stellar/disk wind/jet with the surrounding cloud material.

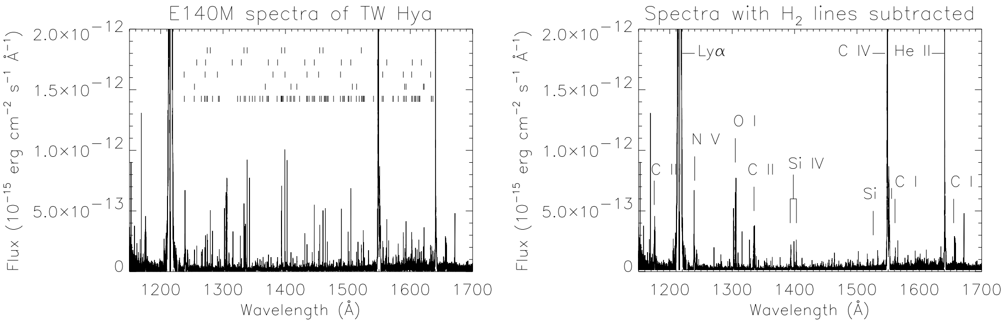

Figure 1. E140M spectrum of TW Hya (left) and the same spectrum after subtracting the H_2 lines (right). To demonstrate the fluorescence, H_2 lines are marked with dashes (left) by upper level, from top to bottom, for vJ=0,1; 1,4; 2,12; 3,16, and all other upper levels. Pairs of dashes show the P and R branches of the particular $v_u - -v_l$ transition.

Weintraub, Kastner, and Bary (2000) reported the detection of H_2 emission in the 1-0 S(1) line at 2.12183 μm from TW Hya, attributing this line to formation in the circumstellar disk in which the H_2 is excited by X-ray ionization from the strong coronal emission of the star (Kastner et al. 1999). Recent images of TW Hya show that the disk is viewed nearly to pole-on (Krist et al. 2000).

2. Observations and Data Reduction

We observed TW Hya with the Space Telescope Imaging Spectrograph on HST on 2001 May 7. We used the medium resolution E140M grating ($R = 45800$) and the $0.5'' \times 0.5''$ aperture ($\sim 28 \times 28$ AU at the 56 pc distance to TW Hya) for a 2300 s integration. We reduced the data using the CALSTIS software package written in IDL (Lindler 1999). We assigned wavelengths with the reduction software using calibrated spectra obtained during the observations. We removed scattered light using the ECHELLE_SCAT routine in the CALSTIS package.

3. Analysis

Figure 1 shows that the TW Hya spectrum is dominated by Lyman B-X transitions of H_2. We detect 174 emission lines in the 1140-1710 Å spectral region (Fig. 1) by fitting either a single Gaussian component or, for blended lines, multiple Gaussians using an algorithm written by Wood (2000, private communication). We correct for instrumental broadening using a line spread function from Sahu et al. (1999). H_2 lines are identified based on coincidence with calculated wavelengths (Abgrall et al. 1993) and fluxes corresponding to branching ratios from similar upper states. We identify 129 H_2 lines from 19 common rovibrational levels in the B electronic state. No CO lines are identified using the Kurucz (1995) database of over 75,000 CO transitions. In the UV, fluorescent

Table 1. H_2 pumping mechanisms

Transition		E_l (cm^{-1})	Transition		E_l (cm^{-1})
P(1) 0-2	1219.368 Å	8194	P(1) 3-3	1217.038 Å	11884
R(0) 0-2	1217.205 Å	8087	R(2) 3-3	1217.031 Å	12085
R(1) 0-2	1217.643 Å	8194	P(3) 3-2	1174.923Å	8723
R(2) 0-2	1219.089 Å	8406	P(14) 3-1	1213.356 Å	14399
P(18) 0-5	1548.146 Å	30458	R(15) 3-1	1214.465 Å	15650
R(10) 0-3	1334.497 Å	16904	P(5) 4-3	1214.781 Å	12779
P(5) 1-2	1216.070 Å	9654	R(6) 4-3	1214.995 Å	13839
R(6) 1-2	1215.726 Å	10261	R(12) 4-2	1213.677 Å	15537
P(11) 1-1	1212.425 Å	10927	P(19) 4-0	1217.410 Å	20958
R(12) 1-1	1212.543 Å	12031	P(13) 2-1	1217.904 Å	13191

CO emission mainly results from pumping by the O I triplet near 1304 Å. The O I triplet in the TW Hya spectrum is weak compared to other lines in the TW Hya spectrum and to O I lines in other stars that show CO fluorescence, such as α Boo (Ayres 1999). CO may also be depleted in the observed region, either because of condensation into grains or dissociation.

The weighted mean redshift of the 129 H_2 lines, using rest wavelengths calculated by Abgrall et al. (1993), is 13.05 ± 0.05 km s^{-1}, consistent with the radial velocity of TW Hya (e.g., Torres 2001). This error bar does not include systematic errors. After subtracting instrumental broadening, the weighted mean width of the H_2 lines is 16.3 ± 0.1 km s^{-1}. The redshift and narrow width of these lines indicate that the H_2 emission may come from the disk.

The rovibrational levels in the B electronic state are populated because certain Lyman-band transitions coincide with strong lines, primarily Lyα. Table 1 shows these transitions and the energy of the lower level from which they were pumped. In steady-state equilibrium, the number of observed downward transitions equals the number of upward transitions. Assuming an optically thin medium, the population of n_l of H_2 in levels of the ground (X) electronic state from which the H_2 is pumped to the B state, is given by

$$n_l = \frac{\sum_{i=1}^{k} \frac{F_i \lambda_i}{hc}}{B_{lu} < J >} 4\pi d^2, \tag{1}$$

where F_i is the observed flux for the k transitions out of the upper state, B_{lu} is the strength of the upward transition pumped by Lyα calculated using Abgrall et al. (1993), d is the distance from the Lyα emission region to the H_2 emission region, and $< J >$ is the flux which pumps the transition, i.e. a Gaussian with a 16 km s^{-1} width convolved with the flux incident upon the H_2 emission region. We correct F_i for transitions outside the observed wavelength region and lines that are absorbed or masked by a stronger line.

A number of routes are pumped by transitions coincident with an interstellar Lyα absorption feature of ~ 500 km s^{-1} FWHM. We assume a variety of intrisic (before IS absorption) Lyα profiles and compare the results. In this paper we assume a profile that generates the best-fit rovibrational populations for a gas at 5000 K. After photoexcitation to the B state, some of the H_2 will ionize and

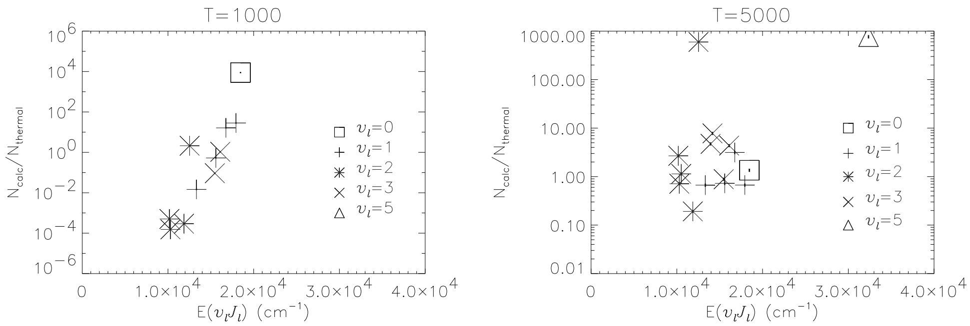

Figure 2. Ratio of observed populations to thermal distributions of H_2 in the X state at 1000 and 5000 K. Error bars, typically ~10%, are included, but are small compared to the range of ratios. The populations are normalized to the sum of the population in the $v_l = 1$ level. No sensible temperature can fit the data.

anywhere from 10 to 25 percent will dissociate (Black & Dalgarno 1976). We assume these factors are uniform across different levels. In a future paper we will treat these effects properly.

We compare this calculated distribution to thermal distributions at various temperatures for 15 of the 19 lower levels(Figure 2), ignoring upper levels that may be pumped from several lower levels. A thermal distribution overestimates the amount of H_2 in low-excitation levels for all temperatures less than 10^4 K, regardless of the shape of the assumed Lyα profile. Thus, we conclude the rovibrational populations of H_2 in the X-state are not in LTE. Moreover, the populations cannot be reproduced with a temperature gradient across the observed region, because all sensible temperature distributions overestimate the population of H_2 in low-excitation levels and underestimate the population in high-excitation levels.

4. Discussion

We have observed fluorescent H_2 and determined that the rovibrational populations in the ground electronic state are non-thermal. Possible excitation mechanisms for the gas include fluorescence, shocks, X-rays and H_2 formation. Each of these mechanisms may occur in the circumstellar disk, although one may be primarily responsible for the excitation of H_2 within the ground electronic state. The highest populated energy level in the X state, $v = 5$, $J = 18$ at $E_l = 30458$ cm^{-1}, is the most difficult to explain. H_2 at this energy has only been previously observed in the IR using ISO (e.g. Rosenthal, Bertoldi & Drapatz 2000); the high excitation of H_2 seen in previous observations is likely produced by shocks.

Pumping of H_2 and its subsequent fluorescence leaves H_2 in excited vibrational levels but will not significantly change its rotational temperature because the allowed transitions have $\Delta J = \pm 1$, while Δv may be large. Non-dissociative shocks typically generate thermal populations at with a distribution of temperatures. However, we have already established that thermal distributions cannot properly reproduce the observed fluorescence. X-rays produce energetic non-thermal electrons that subsequently collisionally excite both rovibrational and electronic levels of H_2. Low vibrational levels are populated directly by the electrons, while higher rovibrational levels are primarily excited from electronic cascade (Tiné et al. 1997). The X-ray flux of $\sim 10^{30}$ erg s^{-1} from TW Hya heats the outer portion of the accretion disk (Glassgold & Najita 2001) and may generate enough energetic electrons to significantly change the rovibrational distribution of H_2. Finally, an H_2 molecule often forms in highly-excited states. Formation of H_2 in the circumstellar environment of TW Hya most likely occurs on grains, which are abundant in the disk beyond about 5 AU (Alessio 2001). The chemistry of the environment may also allow for formation via collisions of H with excited H($n = 2$) or H^- (Rawlings et al. 1993).

The conditions in TW Hya's circumstellar disk may provide the right environment to excite H_2 to energetic levels by X-ray excitation or formation excitation. In a future paper we will model these mechanisms to determine the importance of each mechanism on the rovibrational distribution of H_2.

5. Acknowledgements

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