THE ORIGINS OF FLUORESCENT H₂ EMISSION FROM T TAURI STARS

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ABSTRACT

We survey fluorescent H₂ emission in HST STIS spectra of the classical T Tauri stars (CTTSs) TW Hya, DF Tau, RU Lupi, T Tau, and DG Tau, and the weak-lined T Tauri star (WTTS) V836 Tau. From each of those sources we detect between 41 and 209 narrow H₂ emission lines, most of which are pumped by strong Lyα emission. H₂ emission is not detected from the WTTS V410 Tau. The fluorescent H₂ emission appears to be common to circumstellar environments around all CTTSs, but high spectral and spatial resolution STIS observations reveal diverse phenomenon. Blueshifted H₂ emission detected from RU Lupi, T Tau, and DG Tau is consistent with an origin in an outflow. The H₂ emission from TW Hya, DF Tau, and V836 Tau is centered at the radial velocity of the star and is consistent with an origin in a warm disk surface. The H₂ lines from RU Lupi, DF Tau, and T Tau also have excess blueshifted H₂ emission that extends to as much as −100 km s⁻¹. The strength of this blueshifted component from DF Tau and T Tau depends on the upper level of the transition. In all cases, the small aperture and attenuation of H₂ emission by stellar winds restricts the H₂ emission to be formed close to the star. In the observation of RU Lupi, the Lyα emission and the H₂ emission that is blueshifted by 15 km s⁻¹ are extended to the SW by ~0″07, although the faster H₂ gas that extends to ~100 km s⁻¹ is not spatially extended. We also find a small reservoir of H₂ emission from TW Hya and DF Tau consistent with an excitation temperature of ~2.5 × 10⁴ K.

Subject headings: accretion, accretion disks — circumstellar matter — line: identification — stars: pre–main-sequence — ultraviolet: stars

Online material: machine-readable table

1. INTRODUCTION

Molecular hydrogen is prevalent in both circumstellar disks and nebulosity around young stars. Observationally discriminating between these two sources of H₂ gas could provide a valuable probe of the physical characteristics and evolution of gas in protoplanetary disks. While other probes of this gas, such as CO and H₂O, have yielded powerful insights into the physical conditions of the disk (e.g., Najita et al. 2003; Brittain et al. 2003; Carr et al. 2004), identifying H₂ emission from the disk has been difficult because IR rovibrational transitions are weak, cold H₂ does not radiate, and diagnostics of H₂ gas in the disk can be contaminated by H₂ in surrounding molecular gas.

A variety of methods involving H₂ emission have been used to probe the circumstellar environments around young stars. H₂ emission was first detected around a young star in IR observations (1978). Brown et al. (1981) used IUE to detect far-ultraviolet (FUV, λ < 2000 Å) H₂ emission from T Tau. IR maps of emission in the 1–0 S(1) line and long-slit FUV spectra of H₂ fluorescence reveal that the hot gas extends to 20⁰ from T Tau and is most likely heated by stellar outflows that shock molecular material near the stars (van Langevelde et al. 1994; Walter et al. 2003; Saucedo et al. 2003).

Valenti et al. (2000) detected Lyman-band H₂ emission in 13 of 32 classical T Tauri stars (CTTSs) observed in low-resolution (R ≡ λ/Δλ ≈ 200) FUV spectra obtained with IUE and suggested that most of the nondetections resulted from inadequate sensitivity. Ardila et al. (2002a) found in Hubble Space Telescope (HST) Goddard High Resolution Spectrograph (GHRS) spectra (R = 20,000) of eight CTTSs that the H₂ lines are blueshifted by 0–20 km s⁻¹ relative to the radial velocity of the star. They note that systematic uncertainties in the wavelength calibration of GHRS could be as large as 20 km s⁻¹ for several of their observations that occurred before COSTAR was installed on HST. However, they use the absence of any stars with redshifted H₂ emission to suggest that, for some sources, the blueshift may be significant. This H₂ emission would therefore be produced by stellar outflows. The limited spectral coverage and large (~2⁰) aperture used in the GHRS observations prevented a thorough analysis of the H₂ lines, but Ardila et al. (2002a) confirmed that these lines are pumped by Lyα. Fluorescent H₂ emission is also found from the accreting brown dwarf 2MASSS J1207334–39325 (Gizis et al. 2005). Bary et al. (2003) detected warm H₂ in emission in the 1–0 S(1) line at 2.1218 μm from three of five CTTSs and one of 11 weak-lined T Tauri star (WTTSs). On the basis of kinematics, they suggested that this H₂ emission is produced in the disk within 30 AU of the central star.

Emission in the 2.1218 μm line and the FUV lines is produced by warm (1000–3000 K) gas but not by the cold gas that comprises the bulk of the mass in circumstellar disks. Although H₂ does not radiate at temperatures of ~10 K, emission from 100–500 K gas can be detected in pure rotational H₂ lines. Thi et al. (2001) used ISO to detect emission in the pure rotational H₂ S(1) and S(0) lines at 17 and 28 μm, respectively. However, Richter et al. (2002), Sheret et al. (2003), and Sako et al. (2005) did not detect emission in the S(2) 12 μm line or the S(1) 17 μm line from...
many young stars in their ground-based observations, which used much smaller apertures than ISO. Several of these sources had claimed ISO detections of H$_2$, even though the ground-based nondetections were more sensitive to H$_2$ in a disk than ISO. If the ISO detections are real, then this H$_2$ emission is produced in a molecular cloud or an envelope extended beyond the circumstellar disk. Midway into the analysis of a larger sample, Richter et al. (2004) reported detections of these lines from several young stars including T Tau.

Cold H$_2$ gas can also be observed in absorption from the ground vibrational level at $\lambda < 1120$ Å. However, the detection of H$_2$ absorption through a disk requires that the disk be viewed nearly edge-on yet also be optically thin to FUV emission. The prevalence of H$_2$ absorption toward Herbig AeBe (HAeBe) stars observed with FUSE (Roberge et al. 2001; Lecavelier des Etangs et al. 2003; Bouret et al. 2003; Grady et al. 2004; Martin et al. 2004; Martin-Zaidi et al. 2005) suggests that the H$_2$ absorption toward these massive stars occurs in a molecular cloud or remnant molecular envelope rather than in a disk. For example, based on the observed radial velocity, Martin-Zaidi et al. (2005) suggest that the H$_2$ absorption from HD 141569 is related to the nearby dark cloud L134N. Lecavelier des Etangs et al. (2001) and Roberge et al. (2005) use the absence of any H$_2$ absorption in FUSE spectra to place strong upper limits on the molecular gas mass in the evolved, optically thin disks of TW Hya, AU Mic, and beta Pic.

The E140M echelle spectrograph on the HST Space Telescope Imaging Spectrograph (STIS) provides high-resolution spectra covering a large wavelength range, permitting a detailed analysis of fluorescent H$_2$ emission in the FUV. In a STIS spectrum of TW Hya, Herczeg et al. (2002) detected over 140 H$_2$ lines from 19 distinct upper levels, demonstrating that the Ly$_\alpha$ emission that pumps this H$_2$ emission is broad. The characteristics of this emission and the lack of any other molecular gas near TW Hya suggest that the emission was produced at the disk surface, in a thin layer heated to $T \sim 2500$ K (Herczeg et al. 2002). Although current models of gas in the disk suggest that neither FUV nor X-ray irradiation alone can produce temperatures of 2500 K (Glassgold et al. 2004; Nomura & Millar 2005), together they may sufficiently heat the gas to explain the FUV H$_2$ emission.

In contrast, long-slit HST STIS spectra of T Tau reveal extended H$_2$ emission from only two upper levels that are pumped close to Ly$_\alpha$ line center (Walter et al. 2003; Saucedo et al. 2003), which is similar to the H$_2$ fluorescence detected toward HH 43 and HH 47 (Schwartz 1983; Curiel et al. 1995). The on-source spectrum of T Tau shows a much richer H$_2$ spectrum, similar to that observed toward TW Hya, than is observed off-source (Walter et al. 2003).

The observed FUV spectra of CTTSs are dominated by strong emission in lines of C iv, Si iv, C ii, O i, and many Ly$_\alpha$-pumped H$_2$ lines. Strong Ly$_\alpha$ emission is observed if the small H i column density in our line of sight to the star is small. In addition to these lines, the FUV continuum emission from TW Hya rises at $\lambda < 1650$ Å and is significantly enhanced above the accretion continuum that dominates the NUV emission from CTTSs (Herczeg et al. 2004; Bergin et al. 2004). Bergin et al. (2004) also detected this emission from DM Tau, GM Aur, and LkCa 15. They identify this continuum or pseudocontinuum emission as H$_2$ produced by collisions with energetic electrons, as may be seen from HH 1/2 (Raymond et al. 1997). Bergin et al. (2004) speculate that this FUV continuum may be related to a deficiency of disk emission at $\lambda < 10$ μm, which is caused by the absence of optically thick micron-sized dust within a few AU of the central star (Calvet et al. 2002; D’Alessio et al. 2005). The ongoing accretion requires that the gas in the disk near the star is still present. Eisner et al. (2006) detected optically thin submicron sized dust within 0.06 AU of TW Hya. The source of this H$_2$ continuum emission could be the disk surface, but this remains to be explored. Herczeg et al. (2005) found that the FUV continuum is weak or not present from RU Lupi, even though RU Lupi is a source of strong fluorescent H$_2$ emission.

In this paper, we survey and analyze H$_2$ emission in the FUV spectra of five CTTSs and one weakly accreting WTTS. We report nondetections of H$_2$ emission in the spectra of two WTTSs, only one of which is marginally significant.

In § 2 we describe our observations and in § 3 we describe our targets. In § 4 we present an overview of FUV H$_2$ emission from each source, including line fluxes and pumping mechanisms. In §§ 5 and 6 we analyze the properties of the H$_2$ emission, including spectral and spatial emission profiles, and consider the origin of this emission. Section 7 summarizes our conclusions. The H$_2$ emission from some sources is consistent with a disk origin, but from other sources is consistent with an outflow origin. High spectral and spatial resolution is essential to understanding H$_2$ emission from young stars.

2. OBSERVATIONS

We observed the T Tauri stars DF Tau, RU Lupi, T Tau, DG Tau, V836 Tau, V410 Tau, and V819 Tau with HST STIS as part of HST program GO-8157. Each FUV observation consists of 4–5 orbits using the E140M echelle spectrograph, spanning 1170–1710 Å, with the 0’’2 × 0’’06 aperture to isolate on-source emission. Each visit includes a brief long-slit optical spectrum with the G430L grating, spanning 2850–5750 Å. This program also included several long-slit STIS FUV spectra of T Tau, which were analyzed by Walter et al. (2003). We obtained FUV, NUV, and optical STIS spectra of DF Tau as part of HST program GTO-7718. This FUV observation of DF Tau used the unsupported 0’’5 × 0’’5 aperture, which reduces the spectral resolution but provides more spatial information. We also include and further analyze the HST STIS FUV spectrum of TW Hya (Herczeg et al. 2002) that was obtained as program GTO-8041. Details of these observations are listed in Table 1.

The stars observed with the 0’’2 × 0’’06 aperture were acquired in a 1 s exposure using the F285LP/LP optical long pass filter covering 5500–10000 Å, with a peak sensitivity at 6000 Å. We then peaked up on the sources using an optical white-light mirror and the CCD with the 0’’2 × 0’’06 aperture. For our observations of TW Hya and DF Tau that used the 0’’5 × 0’’5 aperture, the stars were acquired with a narrowband filter (∼90 Å) centered on the [O ii] 3727 Å line. For both TW Hya and DF Tau, the emission in this bandpass consists of the accretion continuum, high Balmer lines also produced by accreting gas, and weak photospheric emission. No peak-up was necessary for these observations.

The pixel size of the FUV MAMA detectors in the E140M echelle mode is 0’’036 (∼3.3 km s$^{-1}$) in the dispersion direction and 0’’029 (1.7 AU at the 57 pc distance of TW Hya and 4 AU at the ~140 pc distance of the other stars in our sample) in the cross-dispersion direction.

We reduced the spectra using the calSTIS pipeline written in IDL (Lindler 1999). We corrected the FUV echelle spectra for scattered light using the echelle_scat routine in IDL. Several steps described below required manual processing.

The automated pipeline processing did not successfully extract the weak spectrum from our observation of DG Tau. We found the spectrum on the detector by searching for the maximum flux in
several H$_2$ lines in the extraction window. Our extraction window is large enough to include any stellar emission, even if the H$_2$ emission is extended only to one side of DG Tau.

As the telescope breathes, the thermal focus changes can modulate the count rate when the point-spread function is larger than the aperture. The observations of RU Lupi and T Tau obtained with the 0′.2 × 0′.06 aperture both exhibit increasing count rates during each orbit that correlate with the improving telescope focus. We calibrate the flux of T Tau following the method that Herczeg et al. (2005) developed for RU Lup. They noted a similar flux increase in E140M observations of the continuum FUV spectrum of V471 Tau (Walter 2004), which were observed through the same small aperture. The 0′.06 slit width is comparable to the width of the point-spread function, and Herczeg et al. (2005) showed that the flux correlates well with the instantaneous FWHM of the target in the cross-dispersion direction. We measured the flux and FWHM of emission in the cross-dispersion direction for several spectral regions in 300 s intervals. These spectral regions are dominated by strong lines of C IV and C IV that are produced by accreting gas and are not extended beyond a point source. The spectral regions do not include a significant contribution from H$_2$ emission, which may be extended (see § 5.2). Figure 1 compares the flux and FWHM in four regions of the T Tau spectrum with those from V471 Tau. We calculate a flux from T Tau of 1.82 × 10$^{-12}$ ergs cm$^{-2}$ s$^{-1}$ in the 1230–1650 Å region and 2.54 × 10$^{-13}$ ergs cm$^{-2}$ s$^{-1}$ in the C IV doublet region (1545–1555 Å). We estimate that the flux calibrations for RU Lupi and T Tau are accurate to ~15%. Since the telescope breathing was not significant during the observations of DF Tau and TW Hya, these spectra are flux-calibrated with an error of at most 10%. Models of the telescope breathing accurately predict the presence or absence of the thermal focus changes for the observations as described above. The low count rates in the observations of DG Tau, V836 Tau, V410 Tau, and V819 Tau prevent us from determining whether they also suffered from the same thermal focus variations as RU Lupi and T Tau. On the basis of the telescopic breathing models we do not expect any significant variations in the point-spread function during those observations, and we estimate that the flux in those observations is accurate to better than 15%.

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**TABLE 1**

| Star   | Date       | Exposure Time (s) | Grating | Aperture (arcsec) | Bandpass (Å) | Spectral Resolution | P.A.$^a$ (deg) |
|--------|------------|-------------------|---------|-------------------|--------------|---------------------|---------------|
| DG Tau | 1999 Sep 18| 72                | G430L   | 52 × 0.2          | 2850–5750    | 1500                | 215           |
| DG Tau | 1999 Sep 18| 1670              | E230M   | 0.2 × 0.2         | 2130–2810    | 3000                | 215           |
| DG Tau | 1999 Sep 18| 2320              | E140M   | 0.5 × 0.5         | 1170–1710    | 2500                | 215           |
| DG Tau | 2000 Jan 28| 36                | G430L   | 52 × 0.1          | 2850–5750    | 1500                | 38            |
| DG Tau | 2000 Jan 28| 9390              | E140M   | 0.2 × 0.06        | 1170–1710    | 45000               | 38            |
| TW Hya | 2000 May 7 | 72                | G430L   | 52 × 0.2          | 2850–5750    | 1500                | 43            |
| TW Hya | 2000 May 7 | 1670              | E230M   | 0.2 × 0.2         | 2130–2810    | 3000                | 43            |
| TW Hya | 2000 May 7 | 2320              | E140M   | 0.5 × 0.5         | 1170–1710    | 2500                | 43            |
| RU Lup  | 2000 Jul 12| 60                | G430L   | 52 × 0.1          | 2850–5750    | 1500                | 41            |
| RU Lup  | 2000 Jul 12| 12530             | E140M   | 0.2 × 0.06        | 1170–1710    | 45000               | 41            |
| V819 Tau | 2000 Aug 30| 180               | G430L   | 52 × 0.1          | 2850–5750    | 1500                | 215           |
| V819 Tau | 2000 Aug 30| 10390             | E140M   | 0.2 × 0.06        | 1170–1710    | 2500                | 215           |
| T Tau  | 2000 Sep 8 | 120               | G430L   | 52 × 0.2          | 2850–5750    | 1500                | 216           |
| T Tau  | 2000 Sep 8 | 12080             | E140M   | 0.2 × 0.06        | 1170–1710    | 45000               | 216           |
| DG Tau | 2000 Oct 22| 120               | G430L   | 52 × 0.1          | 2850–5750    | 1500                | 230           |
| DG Tau | 2000 Oct 22| 12295             | E140M   | 0.2 × 0.06        | 1170–1710    | 2500                | 230           |
| V410 Tau | 2001 Jan 30| 120               | G430L   | 52 × 0.1          | 2850–5750    | 1500                | 32            |
| V410 Tau | 2001 Jan 30| 9590              | E140M   | 0.2 × 0.06        | 1170–1710    | 2500                | 32            |
| V836 Tau | 2001 Feb 14| 180               | G430L   | 52 × 0.1          | 2850–5750    | 1500                | 49            |
| V836 Tau | 2001 Feb 14| 9390              | E140M   | 0.2 × 0.06        | 1170–1710    | 2500                | 49            |

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$^a$ Position angle of cross-dispersion direction.

$^b$ HST Program GO-7718; PI: J. Linsky.

$^c$ HST Program GO-8157; PI: F. Walter.

$^d$ HST Program GO-8041; PI: J. Linsky.

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See http://www-int.stsci.edu/instruments/observatory/focus/ephem.html.

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![Fig. 1.](http://example.com) — Dependence of count rate on the telescope focus. Changes in the telescope focus due to thermal variations alter the count rate in our observations of T Tau because the point-spread function may be wider than the aperture. We calibrate the observed flux by comparing the measured point-spread function and the flux in 300 s time intervals. The point-spread function is the average of the point-spread functions measured in four spectral regions with strong emission lines in the T Tau spectrum (O i 1305 triplet, C n 1335 Å doublet, Si iv 1400 Å doublet, and C IV 1549 Å doublet). The FUV spectrum of V471 Tau is dominated by continuum emission from the white dwarf. We find the best-fit slope from the V471 Tau data and scale the T Tau data to calculate the total flux.
The Doppler correction in the calSTIS data reduction pipeline was in error by a factor of 1.6. We corrected for this problem in the observations of DF Tau, T Tau, and RU Lupi by cross-correlating the spectra obtained within the first 1500 s of each orbit, then subdividing and co-adding each 300–500 s interval over each observation. We then applied this correction to the entire integration for each observation. This method results in a spectral resolution of about 45,000. The low S/N in our observations of DG Tau, V836 Tau, V819 Tau, and V410 Tau prevent the application of this method to correct for the erroneous wavelength shift. Those observations have $R \approx 25,000$. The 0.55 x 0.55 aperture that we used to observe DF Tau and TW Hya is an unsupported mode of STIS. By comparing the H2 spectral profiles of template stars. Because V410 Tau is a spotted, rapidly rotating star with broad and complex absorption lines, its radial velocity is measured less precisely. Our velocity measurements are similar to previous estimates (e.g., Herbig & Bell 1988).

3. SOURCES

Our sample consists of five CTTSs and 3 WTTSs. The CTTSs were selected because they are among the brightest CTTSs observed by IUE and have a range of disk inclinations, mass accretion rates, and circumstellar environments. The three WTTSs were selected to represent varying stages of disk evolution. One WTTS, V836 Tau, retains a disk and is weakly accreting. The WTTSs V410 Tau and V819 Tau show no H2 emission and are only briefly discussed.

The known properties for each of our sources, including the radial velocity ($v_r$), the rotational velocity ($v \sin i$), inclination, and multiplicity, are listed in Table 2. The stellar mass, radius, and temperatures for the Taurus stars may be found in Kenyon & Hartmann (1995). The properties of TW Hya and RU Lupi are listed in Webb et al. (1999) and Herczeg et al. (2005), respectively.

We calculated the accretion luminosity ($L_{\text{acc}}$) at the time of each observation using optical and, for DF Tau and TW Hya, NUV spectra, obtained nearly simultaneously with the FUV observation, and boundary layer accretion models constructed by Valenti et al. (1993). For TW Hya, RU Lupi, T Tau, and DF Tau, we use extinctions ($A_{V}$) calculated from the neutral hydrogen column density in the line of sight to each star, measured from H absorption against LyC emission and H2 absorption detected in FUSE spectra of the stars (cf. Walter et al. 2003; Herczeg et al. 2004). If dust grains in our line of sight to these sources are larger than the average interstellar grain, then $A_{V}$ would be underestimated by $R_{V}/3.1$, where $R_{V}$ is the total-to-selective extinction with an average interstellar value of 3.1 (Cardelli et al. 1989).

### TABLE 2

| Star          | Spectral Type | Class   | $A_{V}$ (mag) | $L_{\text{acc}}$ ($L_{\odot}$) | $M_{\text{acc}}$ ($10^{-3} M_{\odot}$ yr$^{-1}$) | $v_r$ (km s$^{-1}$) | $v \sin i$ (km s$^{-1}$) | Incl. (deg) | Mult. |
|---------------|---------------|---------|---------------|-------------------------------|-----------------------------------------------|---------------------|--------------------------|-------------|-------|
| T Tau N................. | K0            | CTTS    | 0.3$^{b,b}$   | 0.9$^{c}$                      | 4$^{c}$                                       | 18$^{d}$            | 20 $\pm$ 5$^{d}$         | 15$^{e}$     | 3$^{f}$ |
| DF Tau................. | M0            | CTTS    | 0.5$^{b,d}$   | 0.24$^{e}$                     | 3, 0.2$^{e}$                                  | 15$^{e}$            | $\sim$15$^{e}$           | 85$^{f}$     | 2$^{g}$ |
| RU Lupi................. | K7            | CTTS    | 0.07$^{h,g}$  | 0.35$^{i}$                     | 3$^{g}$                                       | $-2^{i}$            | 9.0 $\pm$ 0.9$^{h}$      | 23$^{i}$     | 1–2$^{j}$ |
| DG Tau................. | K7            | CTTS    | 1.6$^{j}$     | 0.22$^{d}$                     | 3$^{d}$                                       | 17$^{f}$            | 37$^{f}$                 | 90$^{f}$     | 3$^{k}$ |
| V410 Tau.............. | K4            | WTTS    | 0.7$^{k}$     | N/A                           | N/A                                           | 33$^{d}$            | $\sim$40$^{d}$           | ...         | 3$^{l}$ |
| V836 Tau.............. | K7            | WTTS    | 0.6$^{k}$     | ...                           | 0.1$^{l}$                                     | 17$^{l}$            | $\sim$15$^{l}$           | ...         | 1$^{m}$ |
| V819 Tau.............. | K7            | WTTS    | 1.5$^{k,n}$   | N/A                           | N/A                                           | 15$^{d}$            | $<10^{d}$                | ...         | 1$^{n}$ |
| TW Hya................. | K7            | CTTS    | 0.0$^{b,n}$   | 0.034$^{o}$                    | 0.2$^{o}$                                     | 13$^{o}$            | $<6^{o}$                 | 7 $\pm$ 1$^{p}$ | 1$^{p}$ |

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The initial wavelength calibration was performed using the on-board Pt/Cr-Ne lamps. We subsequently recalibrated the wavelength shifts by shifting the measured wavelength of the geocoronal Ly$\alpha$ emission line to the predicted location. The relative wavelength calibration within an exposure is accurate to $<0.5$ pixels, or $<1.5$ km s$^{-1}$, and the absolute calibration across exposures is accurate to $<1$ pixel, or $<3$ km s$^{-1}$ (Leitherer et al. 2001). The measured wavelengths of H2 lines from the two DF Tau observations differ by 4 km s$^{-1}$, which is most likely an artifact from our wavelength calibration. We shifted the wavelength scale in these two spectra by 0.25 pixels so that the heliocentric velocities of narrow interstellar O i 1302 Å, C ii 1335 Å, and C ii 1336 Å absorption lines are equal.

To complement our HST observations, we obtained echelle spectra of T Tau, DF Tau, V819 Tau, and V410 Tau with the SOFIN spectrograph at the Nordic Optical Telescope (NOT), covering the entire optical range at $R = 45,000$. We derive the projected rotational velocities and heliocentric radial velocities with an accuracy of $\sim$1.5 km s$^{-1}$ from these spectra and spectra of template stars. Because V410 Tau is a spotted, rapidly rotating star with broad and complex absorption lines, its radial velocity is measured less precisely. Our velocity measurements are similar to previous estimates (e.g., Herbig & Bell 1988).

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Note: 

- $^{a}$ Walter et al. (2003).
- $^{b}$ Calculated from $N$(H), assuming the interstellar relationship of Bohlin et al. (1978), with $R_{V} = 3.1$ (Cardelli et al. 1989). 
- $^{c}$ Calvet et al. (2004).
- $^{d}$ This work.
- $^{e}$ Several references, see text.
- $^{f}$ Johns-Krull & Valenti (2001).
- $^{g}$ Herczeg et al. (2005).
- $^{h}$ Stempels & Piskunov (2002).
- $^{i}$ Stempels et al. (2005).
- $^{j}$ Guillbring et al. (2000).
- $^{k}$ Kenyon & Hartmann (1995).
- $^{l}$ Simon & Prato (1995).
- $^{m}$ White & Ghez (2001).
- $^{n}$ Herczeg et al. (2004).
- $^{o}$ Weintraub et al. (2000).
- $^{p}$ Qi et al. (2004).
3.1. \textit{T} Tau

As the archetype of the entire class of stars, \textit{T} Tau is one of the most studied CTTSs. Walter et al. (2003) and Beck et al. (2004) present an overview of \textit{T} Tau, which is comprised of the optically bright \textit{T} Tau N separated by 0	extdegree 7 from the IR companion \textit{T} Tau Sab.

\textit{T} Tau N contributes all of the flux in the FUV because \textit{T} Tau Sab is heavily obscured (Koresko et al. 1997; Duche
c

Following Herczeg et al. (2004), we measure \( A_V = 1.5 \) mag by fitting the accretion continuum and photospheric emission from \textit{T} Tau, although the anomalously complex NUV continuum is poorly fitted with standard accretion continuum models. An extinction of \( A_V \sim 1.5 \) mag would severely attenuate FUV emission, but emission in the C \( \Gamma \) 977 \AA and O \( \gamma \) 1032 \AA lines was detected by \textit{FUSE} (Wilkinson et al. 2002). Walter et al. (2003) used the total hydrogen column density in the line of sight to \textit{T} Tau N to calculate \( A_V = 0.3 \) mag, which we adopt here.

Various studies suggest an inclination of the disk axis of 8	extdegree–23	extdegree from our line of sight (Herbst et al. 1986, 1997; Eisloeffel & Mundt 1998). IR H\( \alpha \) emission imaged by van Langevelde et al. (1994) and Herbst et al. (1997) and long-slit \textit{HST} STIS FUV spectra obtained by Walter et al. (2003) and Saucedo et al. (2003) show spatially extended H\( \alpha \) emission. Images of shock tracers such as \([\text{Fe} \, \text{ii}]\) and the extended H\( \alpha \) emission reveal an extensive network of nebulosity, including Burnham’s nebula and HH 155, produced by outflows interacting with ambient molecular material (e.g., Herbst et al. 1996, 1997; Stapelfeldt et al. 1998; Solf & Bohn 1999).

The nominal distance to \textit{T} Tau and to the other stars in the Taurus molecular cloud is \( \sim 140 \) pc. Loinard et al. (2005) calculated a distance of 141 \pm 2.8 pc to \textit{T} Tau by measuring the parallax in high-precision astrometric observations of nonthermal radio emission from \textit{T} Tau S.

3.2. DF Tau

DF Tau is a binary system with a separation of 0	extdegree 09 and a position angle of \( \sim 270\) at the time of our observations (White & Ghez 2001; Hartigan & Kenyon 2003; Schaefer et al. 2003; Hartigan et al. 2004). Schaefer et al. (2003) used the decreasing position angle of the pair (300	extdegree in 1994 to 262	extdegree in 2002) to study the orbital motion of the stars. They suggest that the optically bright component, DF Tau A, is the dimmer component in the near-IR. Schaefer et al. (2003) also find that the \( I \)-band emission from the primary star varies by 1.5 mag, while the secondary varies by less than 0.2 mag. They find that the two stars have a similar temperature, mass, and luminosity, but mass accretion rates of \( \sim 10^{-8} \) and \( \sim 10^{-9} \) \( M_\odot \) yr\(^{-1}\) for DF Tau A and DF Tau B, respectively. As a result, DF Tau A dominates the \( U \)-band emission.

Although these characteristics are all consistent with DF Tau A having a higher mass accretion rate than DF Tau B, they could also be explained by invoking a larger extinction to DF Tau B. Furlan et al. (2005) do not find any evidence for disk evolution, either by dust settling or a clearing of the inner disk, from \textit{Spitzer} IRS spectra of DF Tau.

The disk is inclined to our line of sight by 60	extdegree–85	extdegree, based on measurements of \( v \sin i \) and a rotation period of 8.5 days (Hartmann & Stauffer 1989; Johns-Krull & Valenti 2001). Previous extinction estimates range between \( A_V = 0.15 \) and 0.45 mag. (Kenyon & Hartmann 1995; Gullbring et al. 1998; White & Ghez 2001). Following Herczeg et al. (2004), we measure \( N(\text{H} \, \text{i}) = 20.75 \) from the absorption against the red side of the Ly\( \alpha \) emission line. We also estimate \( N(\text{H}_2) = 20.2^{+0.5}_{-0.3} \) from the \( \text{H}_2 \) absorption against the \( \text{O} \, \text{vi} \) and \( \text{C} \, \text{iii} \) emission lines in the \textit{FUSE} spectrum of DF Tau. The uncertainty in this measurement is large because the measurement is inferred indirectly from the weak emission in the \( \text{O} \, \text{vi} \) 1038 \AA line relative to the emission in the \( \text{O} \, \text{vi} \) 1032 \AA line. The \( \text{H}_2 \) excitation temperature is also uncertain. The total hydrogen column density \( N(\text{H}) \sim 20.95 \) corresponds to \( A_V = 0.5^{+0.15}_{-0.2} \) mag, assuming the standard interstellar gas-to-dust ratio (Bohlin et al. 1978). Our line of sight to the star may intercept the flared disk, which could have dust grains larger than is typical for the ISM. Any grain growth in our line of sight, either in a disk or the Taurus molecular cloud, will increase the gas-to-extinction ratio and cause us to underestimate the extinction. On the other hand, the flared disk may be deficient in grains if they have settled to the disk midplane.

In the long-pass optical acquisition image obtained prior to our small-aperture STIS observation of DF Tau, the pair are resolved with a separation of 96 mas and a position angle of 266\textdegree, with DF Tau A being about 13\% brighter than DF Tau B in this band. This separation and position angle are consistent with the relative positions of DF Tau A and B measured by Schaefer et al. (2003) for the same epoch. The peak-up image and the echelle spectra, both obtained with the 0	extdegree 2 \times 0	extdegree 06 aperture, have position angles offset by \( \sim 48\) from the dispersion direction and only include one star. The peak-up presumably found DF Tau A, the brighter of the pair in the CCD.

Only one star is apparent in the acquisition \([\text{O} \, \text{i}]\) image prior to the large-aperture observation of DF Tau. Both stars are included in our 0	extdegree 5 \times 0	extdegree 5 observation of DF Tau with a position angle offset by 51\textdegree from the dispersion direction. The pair may not be resolvable and the secondary is not detected in the FUV. Assuming that DF Tau A dominates emission in the \([\text{O} \, \text{i}]\) filter and in the FUV, then the fainter DF Tau B is located at +6 km s\(^{-1}\) in the dispersion direction. Because the two observations were obtained with a P.A. that differed by 180\textdegree, any spectroscopically resolvable emission contributed by DF Tau B would appear slightly blueshifted in one observation and redshifted in the other observation.

We estimate a mass accretion rate of about 3 \times 10^{-8} \( M_\odot \) yr\(^{-1}\) based on the NUV-optical spectrum obtained just before our observation of DF Tau with the large aperture. During our small-aperture observation, we measured an accretion luminosity about 15 times lower based on the emission in the G430L spectra shortward of the Balmer jump. The optical emission longward of the Balmer jump was about 5 times fainter during the small-aperture observation than in the large-aperture observation. The \( N(\text{H} \, \text{i}) \) and therefore the extinction does not change between the two observations.

The FUV spectrum obtained with the smaller aperture is about 3 times fainter than that obtained with the larger aperture, either because of variability in the mass accretion rate, the different aperture size, or the pointing being slightly offset from DF Tau A. These two observations, obtained with different apertures at different epochs, are analyzed separately.

3.3. \textit{RU} Lupi

\textit{RU} Lupi was discussed in detail by Giovannelli et al. (1995) and Herczeg et al. (2005). Although most previous studies have assumed that \textit{RU} Lupi is a single star, Gahm et al. (2005) detected periodic radial velocity changes of 2.5 km s\(^{-1}\) in photospheric absorption lines, which may indicate the presence of a spectroscopic companion. Indirect evidence indicates that the disk and magnetosphere of \textit{RU} Lupi are probably observed close to pole-on (Giovannelli et al. 1995; Herczeg et al. 2005). Stempels
et al. (2005) derive an inclination of \( \sim 23^\circ \) based on the 3.7 day period and \( v \sin i = 9.0 \text{ km}\ s^{-1} \).

RU Lupi is one of the most heavily veiled CTTSs with a variable H\alpha equivalent width that peaks at 210 Å. Herczeg et al. (2005) described the HST STIS observations of RU Lupi analyzed here. The mass accretion rate onto RU Lupi of \( 3 \times 10^{-7} \) at the time of our observation is high for a K7 CTTS. The outflow from RU Lupi is also very strong, as seen in P Cygni line profiles of neutral, singly ionized, and doubly ionized species. The extinction to RU Lupi is \( A_V \sim 0.07 \text{ mag} \) based on the log \( N(\text{H}) = 20.1 \) to the star (Herczeg et al. 2005). Like Taurus, the Lupus molecular cloud is probably located at 140 pc (de Zeeuw et al. 1999; Bertout et al. 1999).

3.4. DG Tau

DG Tau is a binary CTTS characterized by strong accretion and a powerful bipolar outflow. HST Wide Field Planetary Camera 2 (WFPC2) images of DG Tau reveal an edge-on disk that obscures the star (Krist et al. 1995). The well-studied jets from DG Tau have provided powerful insights into the production of slow and fast winds from CTTSs (e.g., Bacciotti et al. 2002; Anderson et al. 2003; Hartigan et al. 2004). The jet has a position angle of 226° and an inclination to our line of sight of 38° (Bacciotti et al. 2002). In \( \S\ 5 \) we argue that the FUV H\textsubscript{2} emission from DG Tau is produced in an outflow. The FUV spectrum includes very little emission in lines other than H\textsubscript{2}. The long-slit optical spectrum obtained with the 52''/0''2 aperture included the star. The star was acquired with a long-pass optical filter and the optical peak-up succeeded in centering the optical emission. At least some of the X-ray emission from DG Tau is extended beyond the star and likely produced by outflows (Güdel et al. 2005). The FUV emission from DG Tau may also be significantly extended beyond the star. We estimate \( L_{\text{acc}} = 0.22 \ L_\odot \), which corresponds to \( M_{\text{acc}} \sim 3 \times 10^{-8} \ M_\odot \ yr^{-1} \).

We adopt an extinction of \( A_V = 1.6 \text{ mag} \) to DG Tau, based on models of the NUV and \( U \)-band continuum by Gullbring et al. (2000). However, this extinction may apply only to the star itself but not to the warm molecular gas, because the star is viewed through its edge-on disk.

3.5. TW Hya

The namesake of the sparsely populated TW Hya Association (Kastner et al. 1997; Webb et al. 1999), TW Hya is the closest (56 pc) and UV-brightest known CTTS. Even though it is \( \sim 10 \) Myr old (Webb et al. 1999), TW Hya is still weakly accreting, with \( M_{\text{acc}} = 2 \times 10^{-9} \ M_\odot \ yr^{-1} \) at the time of our observations (Herczeg et al. 2004). Since TW Hya is isolated from molecular clouds that are typically associated with CTTSs, the extinction is negligible (Herczeg et al. 2004). Images of the disk reveal that it is observed nearly face-on (Wilner et al. 2000; Krist et al. 2000; Trilling et al. 2001; Weinberger et al. 2002). Qi et al. (2004) used submillimeter observations of the CO \( J = 3-2 \) \( J = 2-1 \) lines to measure an inclination of \( 7^\circ \pm 1^\circ \). The IR spectral energy distribution and \( K \)-band AO imaging on Keck reveals that the dust within 4 AU is optically thin and submicron in size (Calvet et al. 2002; Eisner et al. 2006).

The FUV spectrum of TW Hya was described by Herczeg et al. (2002) and the fluorescent H\textsubscript{2} emission was modeled by Herczeg et al. (2004). Weintraub et al. (2000) measured a flux of \( 1 \times 10^{-15} \) ergs cm\(^{-2}\) s\(^{-1}\) in the rovibrational 1\( -0 \) S(1) line at 2.1218 \( \mu \)m, and Rettig et al. (2004) detected CO emission from TW Hya.

3.6. V819 Tau

V819 Tau shows no significant excess continuum emission at \( \lambda < 12 \mu \text{m} \) but exhibits strong excess emission at 12, 25, and 60 \( \mu \text{m} \), which suggests the presence of a cold disk with a central dust hole (cf. Skrutskie et al. 1990; Wolk & Walter 1996). Bary et al. (2003) placed a flux upper limit of \( 3.0 \times 10^{-15} \) ergs cm\(^{-2}\) s\(^{-1}\) in the 1\( -0 \) S(1) line. The extinction to \( \alpha \) Ori C at \( \lambda \sim 1 \) mag to V819 Tau (Kenyon & Hartmann 1995; White & Ghez 2001) strongly attenuates any FUV emission. We do not discuss this star further.

3.7. V836 Tau

V836 Tau is typically classified as a WTTS, although it has a near-IR excess, indicating the presence of a disk (Mundt et al. 1983; Skrutskie et al. 1990; Skinner et al. 1991; Kenyon & Hartmann 1995; Wolk & Walter 1996). V836 Tau also has H\alpha emission with a variable equivalent width of 9–25 Å (Skrutskie et al. 1990; Hartigan et al. 1995; White & Hillenbrand 2004) and an inverse P Cygni profile (Wolk & Walter 1996), both indicative of accretion. We adopt \( A_V \sim 0.6 \text{ mag} \) to V836 Tau (Kenyon & Hartmann 1995). White & Hillenbrand (2004) estimate a mass accretion rate of \( 10^{-9} \) \( M_\odot \ yr^{-1} \). At the time of our observation, we estimate a mass accretion rate of \( 10^{-9} \) \( M_\odot \ yr^{-1} \) based on the measured C IV flux of \( 1.4 \times 10^{-15} \) ergs cm\(^{-2}\) s\(^{-1}\) and the relationship between \( M \) and C IV flux calculated by Johns-Krull et al. (2000).

3.8. V410 Tau

V410 Tau is a system with three WTTSs that are coronally active and have no detectable IR excess (Kenyon & Hartmann 1995). White & Ghez (2001) measured a separation of 0"07 between the A and B components with an uncertain position angle, and a separation of 0"29 between the A and C components with a position angle of 359°. Since they found that the primary dominates the \( U \)-band emission, we expect that it also dominates the FUV flux. Our FUV observation most likely includes both the A and B components but does not include V410 Tau C.

Kenyon & Hartmann (1995) estimated \( A_V \sim 0.03 \text{ mag} \), while White & Ghez (2001) calculated \( A_V \sim 0.67 \text{ mag} \). Although this disparity is large, it does not significantly impact our analysis. Strong variability in the emission from V410 Tau has been well studied at radio to X-ray wavelengths (e.g., Stelzer et al. 2003; Fernández et al. 2004). Rydgren & Vrba (1983) first reported a 1.87 day period that has been attributed to stellar spots.

4. CHARACTERIZING THE H\textsubscript{2} EMISSION

Strong (\( A_{\text{bol}} \sim 10^8 \text{ s}^{-1} \)) electronic transitions of H\textsubscript{2} occur throughout the FUV wavelength range. Cold H\textsubscript{2} can be excited by photons at \( \lambda < 1120 \) Å, while warmer H\textsubscript{2} can also be excited by photons at longer wavelengths. Lyman-band (B–X) transitions tend to occur at longer wavelengths than Werner-band (C–X) transitions because the B electronic state has a lower energy than the C electronic state. Once electronically excited, the H\textsubscript{2} molecule almost immediately decays to the ground (X) electronic state. The radiative decay from the B electronic state will occur by one of many different transitions that have similar branching ratios. Typically, only a few transitions from the C electronic state have large branching ratios. The H\textsubscript{2} molecule in the B or C electronic state will dissociate by radiative decay to the ground vibrational continuum between 0%–50% of the time, depending on the energy of the upper level.

Warm H\textsubscript{2} gas can absorb photons throughout the FUV. Therefore, a flat radiation field would excite a myriad of upper
levels and produce a pseudocontinuum of densely packed \( \text{H}_2 \) lines. However, the FUV emission from CTTSs is dominated by levels and produce a pseudocontinuum of densely packed \( \text{H}_2 \) emission. Ly\( \alpha \) emission from CTTSs is described in Herczeg et al. (2002). All lines discussed in this paper are Lyman-band lines, except where noted.

Table 3 lists the pumping transitions for the detected emission lines, together with the oscillator strength \( f \), the energy \( E^\nu \) of the lower level of the pumping transition, the theoretical dissociation percentage \( P_{\text{dis}} \) from the upper level calculated by Abgrall et al. (2000), and the velocity of the pumping transition from Ly\( \alpha \) line center. Table 4 lists the number of lines and the total observed flux from each upper level for every source.

Figure 2 shows the observed Ly\( \alpha \) emission and locations of the pumping transitions for each source. For every source discussed here except TW Hya, most or all of the intrinsic Ly\( \alpha \) emission is attenuated by H\( i \) in the interstellar medium and stellar outflows. We do not detect any Ly\( \alpha \) emission from T Tau, DG Tau, V836 Tau, or V410 Tau. We detect only weak Ly\( \alpha \) emission located far from line center from DF Tau and RU Lupi. Only for TW Hya do we detect strong Ly\( \alpha \) emission both longward and shortward of Ly\( \alpha \) line center, because TW Hya is a weak accretor and isolated from molecular clouds that are typically associated with young stars. The strength and large width of the Ly\( \alpha \) emission from TW Hya leads to a more extensive network of observed \( \text{H}_2 \) lines than from the other sources in our sample.

The observation of DF Tau obtained with the small aperture has lower S/N than that obtained with the large aperture and shows fewer lines as a result. No significant differences in \( \text{H}_2 \) emission are detected between those two observations. Several \( \text{H}_2 \) lines pumped by C\( \nu \) from highly excited rovibrational levels in the ground electronic state are discussed in § 4.3.

### 4.1. Identifying \( \text{H}_2 \) Lines

The FUV spectra of the CTTSs TW Hya, DF Tau, RU Lupi, T Tau, and DG Tau, and the WTTS V836 Tau include many narrow \( \text{H}_2 \) emission lines. We do not detect any \( \text{H}_2 \) emission in the spectra of V819 Tau or V410 Tau. We identify \( \text{H}_2 \) lines using the line list of Abgrall et al. (1993). Most of the lines are Lyman-band lines pumped by Ly\( \alpha \), because Werner-band lines pumped by Ly\( \alpha \) are brightest at \( \lambda < 1200 \) Å, where the sensitivity of STIS is low. If one line from an upper level is present, then several other lines with large branching ratios from the same upper level should also be present. In order to positively identify a line as \( \text{H}_2 \), we require that several lines from a given upper level be present with relative fluxes consistent with branching ratios.

Based on models constructed for the \( \text{H}_2 \) fluorescence detected in the TW Hya spectrum (Herczeg et al. 2004; see also § 4.2), we observe fluxes from one or a few lines from an upper level to predict fluxes for all the lines in that progression. These models allow us to identify many weak emission features as \( \text{H}_2 \) lines. Figure 3 shows the observed and model fluxes of 16 lines originating from \( (\nu', J') = (2, 12) \) in the DF Tau spectrum. We use the fluxes in the strongest lines in that progression, such as 2–3 \( \lambda \) 1200; 2–4 \( \lambda \) 1185; and 2–5 \( \lambda \) 1171 Å, to identify and predict the fluxes of the weaker \( \text{H}_2 \) lines, such as 2–1 \( \lambda \) 1185.2 Å and 2–3 \( \lambda \) 1173.5 Å. These models provide a rigorous check on questionable line identifications because they predict the fluxes of all other possible lines from the same upper level.

In rare cases, we identify only one or two lines from a single upper level as Lyman-band \( \text{H}_2 \) lines when the following conditions are met: (1) the lines have an appropriate width and velocity shift, (2) all other lines from the same upper level are either too weak to be detected or are obscured by wind absorption or other emission lines, and (3) we expect emission in that progression based on the observed emission at wavelengths of possible pumping transitions. Generally, only a few Werner-band lines from a single upper level have large branching ratios, and these lines preferentially occur at \( \lambda < 1185 \) Å, where STIS has low sensitivity. Therefore, we relax the requirement of detecting several lines from a single upper level for the identification of Werner-band \( \text{H}_2 \) lines.
TABLE 4
FLUXES IN H2 PROGRESSIONS

| \(v'\)  | \(J'\) | \(\lambda_{\text{pump}}\) (\(\AA\)) | \(v_{\text{trans}}\) (\(\text{km} \text{s}^{-1}\)) | DF Tau | DF Tau | RU Lupi | T Tau | DG Tau | V836 Tau | TW Hydra |
|--------|--------|-----------------------------|-----------------------------|--------|--------|--------|-------|--------|---------|-----------|
|        |       |                             |                             | No.   | \(F_{\text{obs}}\) | No. | \(F_{\text{obs}}\) | No. | \(F_{\text{obs}}\) | No. | \(F_{\text{obs}}\) | No. | \(F_{\text{obs}}\) |
| 1       | 10    | 1212.426                  | -801                        | -      | ...     | -    | ...                | -    | ...                | -    | ...                |
| 1       | 10    | 1212.534                  | -772                        | -      | ...     | -    | ...                | -    | ...                | -    | ...                |
| 3       | 13    | 1213.336                  | -571                        | -      | ...     | -    | ...                | -    | ...                | -    | ...                |
| 4       | 13    | 1213.677                  | -491                        | -      | ...     | -    | ...                | -    | ...                | -    | ...                |

Note.—Fluxes in \(10^{-15} \text{ergs cm}^{-2} \text{s}^{-1}\).

H\textsubscript{2} emission lines were previously identified in the STIS spectra of TW Hydra (Herczeg et al. 2002) and RU Lupi (Herczeg et al. 2005). In this paper, we identify H\textsubscript{2} lines from V836 Tau, T Tau, DG Tau, and two spectra of DF Tau, and we expand the list of H\textsubscript{2} lines observed from TW Hya. Table 5 lists line identifications, fluxes, and branching ratios of observed Lyman-band H\textsubscript{2} emission lines that are pumped by Ly\textsubscript{\alpha} from each star, sorted by progression. Table 6 lists the same properties for highly excited H\textsubscript{2} emission lines that are pumped by C IV. Table 7 lists the blended H\textsubscript{2} lines. In some spectra, lines such as the 1455 Å blend are resolved into two separate lines, while in other spectra we were unable to distinguish between the two lines. Table 8 lists the Werner-band H\textsubscript{2} lines, most of which are also pumped by Ly\textsubscript{\alpha}, although one Werner-band H\textsubscript{2} line from RU Lupi is pumped by strong emission in the O VI 1031 Å line. Outside of regions with strong lines such as C IV or O I, the H\textsubscript{2} line list for TW Hya is complete for \(\lambda > 1200 \text{ Å}\) down to a flux level of \(\sim 4 \times 10^{-15} \text{ergs cm}^{-2} \text{s}^{-1}\), while the H\textsubscript{2} line lists for RU Lupi and DF Tau are complete down to \(\sim 1 \times 10^{-15} \text{ergs cm}^{-2} \text{s}^{-1}\), and that of DG Tau and V836 Tau are complete down to \(4 \times 10^{-16} \text{ergs cm}^{-2} \text{s}^{-1}\). The H\textsubscript{2} lines from T Tau are more difficult to identify because they are broad, which lowers the S/N in each pixel, and are weak relative to many other strong lines in the spectrum, which increases the likelihood of masking by other emission or wind absorption lines. As a result, our H\textsubscript{2} line list for T Tau may not be complete.

Figures 4, 5, 6, and 7 present four spectral regions with strong H\textsubscript{2} lines. The strongest H\textsubscript{2} lines are transitions from the upper levels \((v' J') = (1, 4), (1, 7), (0, 1), (0, 2),\) and \((2, 12)\). These lines are all pumped by transitions located between 0 and 600 \text{km} \text{s}^{-1} from Ly\textsubscript{\alpha} line center (1215.67 Å). The pumping transitions typically have large oscillator strengths and H\textsubscript{2} lower levels with relatively low energies. The locations of the pumping transitions agree with results from Ardila et al. (2002a), who detected only H\textsubscript{2} lines pumped on the red side of Ly\textsubscript{\alpha} in GHR spectra of several CTTSs. TW Hya, RU Lupi, DF Tau, DG Tau, and V836 Tau also exhibit weaker H\textsubscript{2} emission pumped shortward of Ly\textsubscript{\alpha} line center. Many possible pumping transitions are present shortward of Ly\textsubscript{\alpha} and are all detected in the TW Hya spectrum. In the spectrum of DF Tau, we detect H\textsubscript{2} emission from only two levels that are pumped shortward of Ly\textsubscript{\alpha}, and both are pumped at \(v < -300 \text{ km} \text{s}^{-1}\) relative to Ly\textsubscript{\alpha} line center. However, some H\textsubscript{2} lines from DF Tau are pumped at \(v = +1100\). Therefore, the H\textsubscript{2} lines from DF Tau and T Tau indicate that the centroid of the Ly\textsubscript{\alpha} emission that irradiates the warm molecular gas is longward of line center.

As described above, the Ly\textsubscript{\alpha} profile seen by the warm molecular gas differs from the observed Ly\textsubscript{\alpha} emission because of H line attenuation in our line of sight to the star. Some Ly\textsubscript{\alpha} emission may be attenuated by H I prior to irradiating the warm molecular gas. In principle, the H\textsubscript{2} gas may also see a different Ly\textsubscript{\alpha} emission that is longward of line center. Some Ly\textsubscript{\alpha} emission that irradiates the warm molecular gas is longward of line center.
Fig. 2.—Observed Lyα emission from TTSs (shaded). The detected Lyα emission from TW Hya is strong because the H i column density in our line of sight is small. DF Tau and RU Lupi also show some Lyα emission, while the Lyα emission from T Tau, DG Tau, and V836 Tau is completely attenuated in our line of sight by H i in the wind and interstellar medium. The vertical dashed lines, most of which are labeled at the top, indicate the transitions that excite H2 emission for each star. The broad Lyα emission from DF Tau pumps H2 emission primarily in its red wing. Except for TW Hya, the stars show few or no H2 lines pumped by emission shortward of Lyα line center.
than from RU Lupi. DF Tau is viewed edge-on by both the observer and the H2, but TW Hya and RU Lupi are observed face-on by the observer and edge-on by the H2. Therefore, the presence or absence of the red wing in the Ly$\alpha$/C1 line emission profile appears to be independent of viewing angle.

The H2 lines pumped at large velocities from Ly$\alpha$/C1 line center are not detected in IUE spectra of HH 43 and HH 47 (Schwartz 1983; Curiel et al. 1995), or emission extended by up to 20$''$ from T Tau (Walter et al. 2003; Saucedo et al. 2003). Those spectra show H2 emission from only the upper levels (1, 4) and (1, 7) that are pumped at +14 and +99 km s$^{-1}$ from Ly$\alpha$ line center. The accretion processes associated with CTTSs produce much broader Ly$\alpha$ emission than that produced by shocks from interactions between outflows and molecular clouds. Thus, the pattern of H2 fluorescence is a good diagnostic of whether accretion processes or shocks in the interstellar medium provide the Ly$\alpha$ pumping photons.

4.2. H2 Line Fluxes

We fitted the H2 lines with Gaussian profiles to measure the central wavelength, width, and flux. The H2 lines from T Tau and RU Lupi both show significant asymmetric blueshifted emission. We fitted each line from those two sources with one narrow, bright Gaussian component and a fainter broad component that is blueshifted. The width, velocity shift, and percent of the total flux in the weaker component were fixed based on fits to co-added emission lines (see § 5.1). The H2 lines from DF Tau also show a weak blueshifted asymmetry. By fitting single Gaussians to all of the lines from DF Tau, we may be underestimating the true flux by $\sim$5%. This fitting process assumes that the line profile does not depend on the upper level. This method is appropriate for RU Lupi but may result in underestimating the flux in lines originating from $(v', J') = (1, 4)$ and $(1, 7)$ from T Tau and DF Tau (see § 5.1). Tables 5–8 list the H2 lines from each star, sorted by upper level.

Wood et al. (2002) and Herczeg et al. (2004) constructed Monte Carlo models of H2 fluorescence in a plane-parallel slab by computing on the optical depths of the various lines using the branching ratios calculated by Abgrall et al. (1993). Depending on the column density and excitation temperature of the H2 emission region, large line opacities can occur when a low-energy lower level is heavily populated. Transitions from lower levels with large energies remain optically thin because those lower levels have negligible populations. This effect tends to weaken the lines at short wavelengths. These models have been used to probe the temperature $T$ and column density $N$(H2) of the H2 emission region. In this paper, we use the model with the best-fit parameters of $T$ = 2500 K and log $N$(H2) = 18.5 that Herczeg et al. (2004) found for the H2 emission from TW Hya. We apply results from that model here to check our line identifications (§ 4.1) and to estimate fluxes in the undetected lines.

We scale the relative line fluxes predicted by the model to match the observed fluxes, after correcting for extinction. The predicted line fluxes are somewhat uncertain because the physical conditions and the geometry of the warm molecular gas could be different for stars with different emission sources (see § 5.4). Nonetheless, these models explain most of the observed line fluxes successfully. Figures 3–7 compare the observed flux (solid line in Fig. 2 and shaded regions in Figs. 4–7) with the model flux (dashed lines). Tables 5 and 6 list estimates of the
The relative line fluxes are consistent with our adopted extinctions or are too weak to be detected. Masked by strong emission lines, are attenuated by wind absorption.

Although the relative line fluxes are weakly sensitive to extinction, we are unable to improve on the existing extinction estimates because of the low S/N for lines at short wavelengths. The relative line fluxes are consistent with our adopted extinctions in all cases. The H2 lines in the T Tau spectrum indicate A_V < 1.0 mag, which suggests that the lower extinction value toward T Tau of A_V = 0.3 mag adopted here is appropriate.

The observed H2 fluxes from DF Tau are 2.5–3 times lower in our observation with the small aperture compared to the observation with the large aperture, but the Lyα emission was only 1.73 times smaller. Since H2 is pumped by Lyα, the observed H2 fluxes should be directly proportional to the strength of Lyα emission. However, we cannot draw any significant conclusions from this discrepancy because the large aperture contains both stars, while the small 0.2 × 0.06 aperture contained only one star.

Table 9 lists the observed flux, not corrected for extinction, in strong FUV emission lines and in the strongest five H2 progressions. The typical ratio of observed C IV to H2 flux in the strongest progression is about 7:1. We therefore expect that between two and five progressions from the WTTS V410 Tau should have fluxes >4 × 10^{-15} ergs cm^{-2} s^{-1}. We place flux upper limits of (1–2) × 10^{-15} ergs cm^{-2} s^{-1} in each progression from V410 Tau by finding flux upper limits for individual emission lines and then applying the models described above to calculate an upper flux limit in the entire progression. These upper limits are about a factor of 2 below the H2 flux we crudely expect from the previously described correlation with C IV emission. We conclude that a significant reservoir of warm H2 is probably not present around V410 Tau. Since a large extinction attenuates almost all of the FUV emission from the WTTS V819 Tau, the nondetection of H2 from this star is not significant.

### 4.3. Highly Excited H2

Most of the detected H2 lines are photoexcited from lower levels in the ground electronic state with energies of 1–2 eV. These

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**TABLE 5**

LYMAN-BAND H2 LINES, LISTED BY PROGRESSION

| ID         | \(\lambda_{calc}\) (Å) | \(f_n^a\) | TW Hya | DFb Tau | DFc Tau | RU Lupi | T Tau | DG Tau | V836 Tau |
|------------|-------------------------|-----------|--------|---------|---------|---------|-------|--------|----------|
| 1–2 P(11) | 1267.222                | 0.084     | 2.2    | ...     | ...     | ...     | ...   | ...    | ...      |
| 1–3 R(9)  | 1292.448                | 0.088     | 4.9    | ...     | ...     | ...     | ...   | ...    | ...      |
| 1–3 P(11) | 1323.232                | 0.076     | 3.8    | ...     | ...     | ...     | ...   | ...    | ...      |
| 1–4 R(9)  | 1348.619                | 0.034     | 2.3    | ...     | ...     | ...     | ...   | ...    | ...      |
| 1–6 R(13) | 1462.148                | 0.051     | 3.8    | ...     | ...     | ...     | ...   | ...    | ...      |
| 1–6 P(11) | 1494.193                | 0.080     | 4.8    | ...     | ...     | ...     | ...   | ...    | ...      |
| 1–7 R(9)  | 1518.134                | 0.106     | 5.6    | ...     | ...     | ...     | ...   | ...    | ...      |
| 1–8 R(9)  | 1572.320                | 0.079     | 4.5    | ...     | ...     | ...     | ...   | ...    | ...      |
| 1–8 P(11) | 1603.095                | 0.059     | 9.7    | ...     | ...     | ...     | ...   | ...    | ...      |

**Note:** Flux in 10^{-15} erg cm^{-2} s^{-1}. The total flux in a progression, here termed model flux, may be larger than the extinction-corrected observed flux because of unseen lines. Table 5 is available in its entirety in the electronic edition of the Astrophysical Journal Supplement. A portion is shown here for guidance regarding its form and content.

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**TABLE 6**

HIGHLY EXCITED H2 LINES, LISTED BY PROGRESSION

| ID         | \(\lambda_{calc}\) (Å) | \(f_n^a\) | TW Hya | DF Tau |
|------------|-------------------------|-----------|--------|--------|
| 0–2 P(25) | 1498.007                | 0.049     | 2.9    | 1.0    |
| 0–4 R(23) | 1524.241                | 0.168     | 4.0    | 1.3    |
| 0–4 P(25) | 1594.059                | 0.180     | 5.4    | 2.1    |
| 0–5 R(23) | 1586.688                | 0.168     | 1.5    |        |
| Total observed flux | 12.3 | 5.9 |        |        |
| Extinction-corrected flux | 12.3 | 19.6 |        |        |
| Model flux | 24.0 | 26.0 |        |        |

**Note:** Flux in 10^{-15} erg cm^{-2} s^{-1}. The total flux in a progression, here termed model flux, may be larger than the extinction-corrected observed flux because of unseen lines.
levels are populated sufficiently with excitation temperatures of $T = 2000$–$3000$ K to explain the observed emission (Black & van Dishoeck 1987; Wood et al. 2002; Herczeg et al. 2004). Herczeg et al. (2002) detected emission from the $(v',J') = (0,17)$ and $(0,24)$ levels from TW Hya, yet these upper levels cannot be excited by Ly$\alpha$. We confirm the presence of these lines in the spectra of both TW Hya and DF Tau. We also identify the strongest line in FUV spectra of CTTSs, after Ly$\alpha$ (van Dishoeck & Wood 1987; Herczeg et al. 2004). The amount of emission absorbed by an H$_2$ transition, $F_{H_2}$, is given by

$$F_{H_2} = \eta F_{\text{pump}} \int_{\lambda} \left(1 - e^{-\tau_{N(H_2)}}\right) d\lambda,$$

where $F_{\text{pump}}$ is the flux at the pumping wavelength, $\eta$ is the solid angle filling factor of H$_2$ as seen from the Ly$\alpha$ emission region, assumed to be $0.25$ (Herczeg et al. 2004), and $N(H_2)$ is the temperature and column density of the slab, and the integral is the effective equivalent width of the transition. The entire FUV spectrum is required to calculate the excitation of every upper level of H$_2$. We used the STIS spectrum of TW Hya to estimate the flux at $\lambda > 1187$ Å, and a $F$-band spectrum of TW Hya to estimate the flux at $\lambda < 1187$ Å (FUSE Program C067, PI: J. L. Linsky). Among the many models run, we present results for synthetic spectra based on an H$_2$ layer with log $N(H_2) = 18.5$ (units cm$^{-2}$) and $T = 2500$ K (our standard model), and that standard model with an additional layer of log $N(H_2) = 17.0$ and $T = 2.5 \times 10^4$ K. Differences between the two model spectra are attributed to the small reservoir of highly excited gas. We also calculate spectra for models of gas that is irradiated by

We investigated the excitation conditions required to produce this emission by forward modeling the H$_2$ spectrum. We constructed synthetic H$_2$ spectra by modeling a isothermal, plane-parallel slab of H$_2$ following the procedure described by Wood et al. (2002) and Herczeg et al. (2004). The amount of emission absorbed by an H$_2$ transition, $F_{H_2}$, is given by

$$F_{H_2} = \eta F_{\text{pump}} \int_{\lambda} \left(1 - e^{-\tau_{N(H_2)}}\right) d\lambda,$$

where $F_{\text{pump}}$ is the flux at the pumping wavelength, $\eta$ is the solid angle filling factor of H$_2$ as seen from the Ly$\alpha$ emission region, assumed to be $0.25$ (Herczeg et al. 2004), and $N(H_2)$ is the temperature and column density of the slab, and the integral is the effective equivalent width of the transition. The entire FUV spectrum is required to calculate the excitation of every upper level of H$_2$. We used the STIS spectrum of TW Hya to estimate the flux at $\lambda > 1187$ Å, and a $F$-band spectrum of TW Hya to estimate the flux at $\lambda < 1187$ Å (FUSE Program C067, PI: J. L. Linsky). Among the many models run, we present results for synthetic spectra based on an H$_2$ layer with log $N(H_2) = 18.5$ (units cm$^{-2}$) and $T = 2500$ K (our standard model), and that standard model with an additional layer of log $N(H_2) = 17.0$ and $T = 2.5 \times 10^4$ K. Differences between the two model spectra are attributed to the small reservoir of highly excited gas. We also calculate spectra for models of gas that is irradiated by

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**TABLE 7**

Identification and Fluxes of Blended H$_2$ Lines

| $\lambda$ (Å) | ID | TW Hya | DF$^a$ Tau | DF$^b$ Tau | RU Lupi | T Tau | DG Tau | V836 Tau |
|---------------|----|--------|------------|------------|---------|-------|--------|----------|
| 1266.9        | 4–4 $P(5)$ | 4–1 $P(19)$ | 13.1 | 1.3 | 0.40 | ... | ... | ... | ... |
| 1320.2        | 3–2 $P(18)$ | 5–7 $P(6)$ | ... | 2.2 | ... | ... | ... | ... | ... |
| 1408.8        | 1–5 $P(8)$ | 3–4 $P(17)$ | ... | ... | 1.8 | ... | ... | ... | ... |
| 1429.7        | 2–5 $R(14)$ | 3–5 $R(16)$ | 4.6 | 1.5 | ... | ... | ... | ... | ... |
| 1454.9        | 0–6 $R(0)$ | 0–6 $R(1)$ | ... | ... | 4.0 | 0.51 | ... | ... | ... |
| 1493.7        | 0–4 $P(18)$ | 0–3 $R(23)$ | 4.7 | 0.8 | 1.7 | 3.7 | 1.3 | 0.39 | ... |
| 1516.2        | 0–7 $R(0)$ | 0–7 $R(1)$ | 22.0 | 5.4 | ... | ... | ... | ... | ... |
| 1522.8        | 3–7 $P(14)$ | 3–7 $R(16)$ | 5.2 | ... | ... | ... | ... | ... | ... |
| 1572.7        | 4–10 $P(5)$ | 2–8 $P(11)$ | 8.3 | ... | ... | ... | ... | ... | ... |
| 1576.9        | 2–8 $R(14)$ | 0–8 $R(0)^b$ | 15.1 | ... | ... | ... | ... | ... | ... |
| 1585.8        | 4–10 $P(8)$ | 0–8 $P(23)$ | 7.4 | 3.9 | ... | ... | ... | ... | ... |
| 1586.8        | 4–10 $P(12)$ | 0–5 $P(23)$ | 10.8 | ... | ... | ... | ... | ... | ... |

**Note.**—Flux in $10^{-15}$ ergs cm$^{-2}$ s$^{-1}$.  
$^a$ Data obtained with the $0.5\times0.5$ aperture.  
$^b$ Data obtained with the $0.2\times0.06$ aperture.  
$^c$ Also 0–8 $R(1)$.  
$^d$ Also 0–10 $R(1)$.  
$^e$ Also 0–2 $Q(10)$, pumped by 0–4 $Q(1)$ 1217.263 Å.  
$^f$ Also 0–2 $Q(1)$, pumped by 2–6 $R(1)$ 1217.298 Å, and 1–4 $Q(7)$, pumped by 1–5 $Q(7)$ 1218.508 Å.

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**TABLE 8**

Identification and Fluxes of Werner-Band H$_2$ Lines

| $\lambda$ (Å) | ID | TW Hya | DF Tau$^a$ | RU Lupi | Pump |
|---------------|----|--------|------------|---------|------|
| 1154.910      | 1–3 $P(11)$ | 12.3 | ... | ... | 1–5 $R(9)$ 1216.997 Å |
| 1172.00        | 1–4 $R(5)$ | 7.5 | 2.9 | ... | 1–5 $P(5)$ 1216.988 Å |
| 1174.4         | 1–3 $R(9)$ | 5.6 | ... | ... | 1–5 $R(9)$ 1216.997 Å |
| 1186.226       | 1–4 $R(12)$ | 4.9 | ... | ... | 1–4 $P(14)$ 1214.566 Å |
| 1208.932       | 1–5 $Q(3)$ | 2.2 | ... | ... | 1–1 $Q(3)$ 1031.862 Å |
| 1228.406       | 2–6 $P(5)$ | 1.3 | ... | ... | 2–6 $P(3)$ 1217.488 Å |
| 1255.507       | 1–5 $P(14)$ | 5.88 | ... | ... | 1–4 $P(14)$ 1214.566 Å |

**Note.**—Flux in $10^{-15}$ ergs cm$^{-2}$ s$^{-1}$.  
$^a$ Data obtained with the $0.5\times0.5$ aperture.  
$^b$ Also 0–3 $Q(10)$, pumped by 0–4 $Q(1)$ 1217.263 Å.  
$^c$ Also 0–2 $R(1)$, pumped by 2–6 $R(1)$ 1217.298 Å, and 1–4 $Q(7)$, pumped by 1–5 $Q(7)$ 1218.508 Å.
all FUV photons except for Lyα. Figure 8 compares the observed TW Hya spectrum to three of these models. The H2 lines from the (0, 17), (0, 24), and (1, 14) upper levels are produced by photoexcitation by C IV in the highly excited layer of H2. Lines in these three progressions are the strongest Lyman-band lines that are not pumped by Lyα/C11. On the basis of these models, we find many other weak features in the spectrum that could also be attributed to pumping by C IV, C II, and several other strong emission lines. While the temperature and column density for this hot layer are poorly constrained at present, these results demonstrate the need for a thin layer of highly excited H2 to explain these lines.

With the presence of the highly excited H2 layer, our models predict that many undetected H2 lines should be much stronger than the weak lines from (0, 17), (0, 24), and (1, 14). Since all of these undetected lines should be pumped by Lyα, we are forced to conclude that somehow Lyα photons are prevented from irradiating the bulk of the highly excited H2 gas. This observational result is unexpected and not easily explained. We therefore suggest a highly speculative possible explanation, although there may be other more physical explanations. In principle, the highly excited H2 could be mixed in with both the warm (~2500 K) H2 layer and colder gas below. Scattering by H I in the warm surface layer could then increase the path length of Lyα photons, leading to preferential attenuation of Lyα emission by dust. In this case, the FUV radiation field that irradiates the gas beneath the thin surface layer may be dominated by emission in lines such as C IV. We caution the reader that this speculative scenario is outlined here only to describe the a process that could irradiate a surface with C IV but not Lyα emission.

The highly excited H2 emission is detected from two sources, TW Hya and DF Tau, which have strong FUV continuum emission, but it is not detected from RU Lupi, which does not have a strong FUV continuum. Since the FUV continuum is likely produced by electron excitation of H2 (Bergin et al. 2004), it could be related to the highly excited H2. Electronic excitation of H2, like FUV pumping, will result in significant vibrational excitation but not significant rotational excitation. However, if the H2 formation rate is sufficiently large, it could produce a population of H2 in highly excited rovibrational levels. H2 may form by many routes, including on grains in gas at T < 500 K, by associative detachment of H/C0, or by dissociative recombination of H+. These and other H2 formation processes produce a population of highly excited H2 (e.g., Takahashi et al. 1999; Bieniek & Dalgarno 1979; Kokouline et al. 2001).

4.4 Variability of H2 Emission from T Tau

Walter et al. (2003) detected emission in the red wing of the Lyα line in two of three long-slit G140L spectra of T Tau obtained in our program, but no Lyα emission in the echelle spectrum of T Tau. Only this red wing is seen because the core is absorbed by interstellar H I, and any blueshifted emission is absorbed in the stellar winds. The nondetection of any Lyα emission in two of the four spectra is the result of either a variable Lyα line width or a variable H I column density in our line of sight. Walter et al. (2003) conclude that these changes are not caused...
Fig. 5.—Same as Fig. 4 for the spectral region 1332–1343 Å. This region is dominated by the C ii doublet, as seen in strong redshifted emission and blueshifted absorption. The wavelength extent of wind absorption in both the C ii 1334.5 and the C ii 1335.7 Å lines is shown by the arrows. The narrow absorption feature near line center of C ii is produced by the interstellar medium.

Fig. 6.—Same as Fig. 4 for the spectral region 1393–1404 Å. The Si iv resonance doublet can be quite strong and mask several H$_2$ emission lines, as is seen in the RU Lupi and T Tau spectra. In the spectra of DF Tau and TW Hya, Si iv emission is weak and the region is instead dominated by strong H$_2$ lines.
by a different H\textsc{i} column density in our line of sight because the shape of the Ly\textsc{α} profile did not change, even though the detected Ly\textsc{α} line strength was different in the two observations. We confirm this result by relating the presence of emission in the red wing of Ly\textsc{α} to the relative flux in each progression. Figure 9 shows the Ly\textsc{α} and 1400–1500 Å regions for our three long-slit spectra and our echelle spectrum, convolved to the spectral resolution of G140L (\(R \sim 1000\)). We scale the observed emission to equal the flux in every observation between 1495 and 1510 Å, a region dominated by several strong H\textsc{2} lines from (1, 4) and (1, 7). Based on the strength of the extended H\textsc{2} emission, at most 10\% of the on-source emission in H\textsc{2} lines from (1, 4) and (1, 7) is related to the extended shocks seen in long-slit spectra. The relative flux of H\textsc{2} emission lines from the same upper level also remains constant during the four observations. A higher extinction in an observation would suppress lines at shorter wavelengths. We conclude that the extinction to T Tau remains constant during these observations. When the redshifted Ly\textsc{α} emission disappears, the relative H\textsc{2} emission in lines from (0, 1), (0, 2), and (2, 12) decreases substantially, relative to that from (1, 4) and (1, 7). The echelle observation shows the strongest emission in hot accretion lines such as C\textsc{iv}, H\textsc{2} lines from (1, 4) and (1, 7), and the continuum but has no detectable redshifted Ly\textsc{α} emission and as a result shows the weakest absolute flux in H\textsc{2} lines from (0, 1), (0, 2), and (2, 12). Since the lines from (0, 1), (0, 2), and (2, 12) are pumped at +379, +487, and +551 km s\textsuperscript{-1}, respectively, from Ly\textsc{α} line center, the strength of these lines probe the strength of the transitions.

**TABLE 9**

**Fluxes in Strong Lines and H\textsc{2} Progressions**

| Star      | C\textsc{iv} 1549 Å | Si\textsc{iv} 1400 Å | C\textsc{ii} 1335 Å | O\textsc{i} 1305 Å | He\textsc{ii} 1640 Å | H\textsc{2} (1, 4) | H\textsc{2} (1, 7) | H\textsc{2} (0, 1) | H\textsc{2} (0, 2) | H\textsc{2} (2, 12) |
|-----------|----------------------|----------------------|---------------------|-------------------|------------------------|----------------|----------------|----------------|----------------|----------------|
| TW Hya    | 284                  | 11                   | 11                  | 95                | 1.4                    | 38             | 17             | 41             | 43             | 19             |
| RU Lupi   | 70                   | 69                   | 11                  | 26                | 7.6                    | 9.2            | 4.7            | 5.4            | 6.1            | 3.1            |
| DF Tau (large) | 33               | 2.5                  | 4.3                 | 5.6               | 8.1                    | 5.2            | 2.2            | 7.0            | 12.3           | 8.4            |
| DF Tau (small) | 2.9              | 0.38                 | 0.78                | 1.6               | 0.82                   | 1.6            | 0.89           | 2.4            | 4.2            | 3.0            |
| T Tau     | 22.6                 | 5.6                  | 2.5                 | 25                | 5.5                    | 1.8            | 1.6            | 2.5            | 3.8            | 2.0            |
| DG Tau    | <0.08                | <0.05                | <0.04               | 0.09              | <0.07                  | 0.30           | 0.19           | 0.48           | 0.86           | 0.46           |
| V836 Tau  | 1.4                  | 0.13                 | 0.38                | 0.44              | 0.84                   | 3.9            | 1.6            | 4.2            | 3.5            | 2.1            |
| V410 Tau  | 2.8                  | 0.88                 | 1.2                 | 1.1               | 1.7                    | <0.3           | <0.16          | <0.08          | <0.2           | <0.2           |
| V819 Tau  | <0.2                 | <0.2                 | <0.1                | <0.2              | <0.08                  | <0.2           | <0.2           | <0.07          | <0.2           | <0.2           |

*Note.*—Flux in 10\textsuperscript{-14} ergs cm\textsuperscript{-2} s\textsuperscript{-1}, not corrected for extinction.
red wing of Lyα. The lines from (1, 4) and (1, 7), which are pumped at +99 and +14 km s$^{-1}$, depend on the emission near Lyα line center. The changes in the intrinsic Lyα profile are seen both directly in our observations and by the H$_2$ gas, even though we are viewing the system face-on, while the H$_2$ is likely viewing the star with a large inclination.

5. CONSTRAINTS ON THE ORIGIN OF THE H$_2$ EMISSION

In this section, we analyze the spectral and spatial properties of the H$_2$ emission to identify the source of the H$_2$ emission. Strong lines within each progression are co-added for each star to improve the S/N in the spectral profiles. We consider only lines in the five strongest progressions, from $(v', v) = (1, 4)$, (1, 7), (0, 1), (0, 2), and (2, 12).

We group the lines from (1, 4) and (1, 7) together because these progressions are pumped at +99 and +14 km s$^{-1}$ from Lyα line center, and consequently may be excited by a narrow Lyα emission line. The progressions from (0, 1), (0, 2), and (2, 12) are grouped together because they are pumped by transitions between 380 and 550 km s$^{-1}$ from Lyα line center, which requires broad Lyα emission.
The telescope thermal focus variations make the point-spread function of HST uncertain (see §2). The spatial profiles of the hot lines of C \textsc{iv} and Si \textsc{iv} are most likely produced at or near the accretion shock (Johns-Krull et al. 2000; Calvet et al. 2004) and should approximate the point-spread function. The strong lines produced in cooler gas, such as O \textsc{i} and C \textsc{ii}, are also not spatially extended and can be used as a proxy for the point-spread function. The point-spread function of STIS can depend on wavelength, particularly with the 0\textsuperscript{B}5 aperture, so when possible we compare the spatial profile of lines located near each other. This method is sensitive to emission extended beyond the hot emission lines but is not sensitive to reflection of FUV emission from a disk surface or nebulosity. Figure 12 shows the spatial distributions of various lines from DF Tau, T Tau, and RU Lupi. We also construct space-velocity diagrams to analyze the spatial distribution of co-added H\textsubscript{2} emission across the line profile.

5.2.1. DF Tau

We concentrate on the observation of DF Tau obtained with the 0\textsuperscript{B}5 aperture, because the S/N in H\textsubscript{2} and other emission lines is higher than in the observation taken with the 0\textsuperscript{B}2 aperture. All results are consistent with the observations that used the small aperture.

Figure 12 shows that the H\textsubscript{2} emission lines between 1270–1400 Å (top left) and 1500–1650 Å (bottom left) have a similar profile to the C \textsc{ii} and C \textsc{iv} emission lines, respectively. The spatial profiles of this emission are well characterized by the combination of a narrow and a broad Gaussian profile. We measure an instrumental spatial resolution of 0\textsuperscript{B}10 (0.36 pixels or 14.6 AU at the distance of DF Tau) and 0\textsuperscript{B}14 (0.47 pixels or 19.0 AU). We identify weak asymmetric emission in the wings of several lines, including C \textsc{i} and C \textsc{iv}, offset from the emission peak by about 0\textsuperscript{B}17. The spatial separation indicates that this emission is not directly associated with the secondary star. The disk of DF Tau is observed close to edge-on. Because dust strongly forward scatters FUV emission (Draine 2003), in principle one side of the disk could scatter such extended emission. This emission component may instead be an artifact from an asymmetric point-spread function.

Figure 13 shows the space-velocity diagram for DF Tau for the observations obtained with the large aperture (left) and small aperture. All results are consistent with the observations that used the small aperture.

Fig. 9.—Ly\textsubscript{o} and H\textsubscript{2} emission in four spectra of T Tau, scaled by the flux between 1495 and 1510 Å. We previously obtained three long-slit G140L spectra of T Tau, with dates labeled (Walter et al. 2003). We convolve the E140M echelle spectrum (shaded) to the resolution of G140L (R = 1000). The Ly\textsubscript{o} emission is strong in the observations obtained on 2000 November 26 and 2000 December 1 but is not present in the echelle spectrum (the apparent bump at 1220 Å is noise, see Fig. 2) or the spectrum obtained on 2001 January 5. As can be seen at 1455–1465 and 1515–1525 Å, when Ly\textsubscript{o} emission is not present the H\textsubscript{2} emission from (v', j') = (0, 1) and (0, 2), marked by dashed vertical lines are much weaker relative to the H\textsubscript{2} emission from (1, 4) and (1, 7), marked by the dotted vertical lines. Because lines from (0, 1) and (0, 2) are pumped by the red wing of Ly\textsubscript{o}, we infer that the intrinsic Ly\textsubscript{o} profile is narrower during those observations.
Fig. 10.—Spectral profiles of H$_2$ lines from upper levels $(v', J' = (0, 1), (0, 2), (2, 12))$, shifted in velocity so that line center is at $v = 0$. The H$_2$ lines from RU Lupi, DF Tau, and T Tau all show a significant blueshifted component. Dotted lines indicate the instrumental line-spread function. The blueshift from DF Tau is evident in both observations, which had position angles that differed by 180°, so the blueshift is real and not a spatial displacement of the secondary star in the dispersion direction.

**TABLE 10**

| Star      | $(v', J')$          | Component | $r_{H_2}$ | FWHM | Flux Fraction$^b$ |
|-----------|---------------------|-----------|-----------|------|-------------------|
| DF Tau    | (0, 1); (0, 2); (2, 12) | 1         | −1        | 23   | N/A               |
| DF Tau    | (1, 4); (1, 7)      | 1         | −8        | 41   | N/A               |
| DF Tau$^e$| (0, 1); (0, 2); (2, 12) | 1         | 6         | 19   | 0.70              |
| DF Tau$^e$| (0, 1); (0, 2); (2, 12) | 2         | −8        | 30   | 0.30              |
| DF Tau$^e$| (0, 1); (0, 2); (2, 12) | 1         | 3         | 24   | N/A               |
| DF Tau    | (1, 4); (1, 7)      | 1         | 0         | 36   | N/A               |
| RU Lupi   | All                 | 1         | −12       | 18   | 0.57              |
| RU Lupi   | All                 | 2         | −30       | 53   | 0.43              |
| T Tau     | (0, 1); (0, 2)      | 1         | −12       | 28   | 0.64              |
| T Tau     | (0, 1); (0, 2)      | 2         | −72       | 65   | 0.36              |
| T Tau     | (1, 4); (1, 7)      | 1         | −2        | 30   | 0.49              |
| T Tau     | (1, 4); (1, 7)      | 2         | −65       | 69   | 0.51              |

$^a$ Component of fit, if the fit used multiple Gaussians.
$^b$ Fraction of flux in a component, where applicable.
$^c$ Large aperture.
$^d$ Small aperture.
$^e$ Lines fitted as both a single and double Gaussian.
The solid lines are contours of 0.2, 0.5, and 0.8 times the peak flux for emission from (0, 1), (0, 2), and (2, 12). The shaded regions show the same contours for lines from (1, 4) and (1, 7). The lines pumped near Ly$\alpha$/C$\text{I}$ line center, from (1, 4) and (1, 7), may be slightly more extended in the SW direction than the other H$_2$ lines.

5.2.2. RU Lupi

Figure 12 compares the spatial extent of H$_2$ emission from RU Lupi between 1270–1400 Å (top) and 1500–1650 Å (bottom) with that of Ly$\alpha$, Si iv, and C iv. The H$_2$ and Ly$\alpha$ emission is extended to the SW. No other FUV emission lines, including Ly$\alpha$-pumped Fe ii emission, appear extended beyond a point source. Figure 14 shows a space-velocity diagram of co-added H$_2$ emission from RU Lupi. The shaded regions show contours of 0.2, 0.5, and 0.8 times the peak emission. The solid lines show contours of 0.2, 0.5, and 0.8 times the peak emission at each pixel in the spectra direction and therefore indicate the spatial distribution of emission across the line profile. The dashed lines indicate the point-spread function measured from Si iv emission. The H$_2$ emission at $\sim 15$ km s$^{-1}$ is extended in the SW direction but not in the NE direction. About 70% of this emission at $\sim 15$ km s$^{-1}$

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**Table 11**

**GLOBAL PROPERTIES OF H$_2$ EMISSION**

| Star      | $v_{HI}$ | FWHM | Number of Upper Levels | Number of Lines | $F_{\text{obs}}$ | $F_{\text{ext}}$ | $F_{\text{mod}}$ |
|-----------|----------|------|------------------------|----------------|-----------------|-----------------|-----------------|
| DF Tau$^a$| $-1$     | 23.2 | 22                     | 164            | 51.0            | 188             | 210             |
| DF Tau$^b$| $6$      | 18.6 | 13                     | 94             | 14.4            | 53.5            | 62.1            |
| RU Lup    | $-12$    | 17.6 | 13                     | 88             | 28.5            | 34.3            | 48.3            |
| T Tau     | $-12$    | 28.4 | 7                      | 41             | 9.26            | 20.2            | 29.2            |
| DG Tau    | $-27$    | 26.1 | 10                     | 58             | 2.55            | 152$^e$         | 210             |
| V836 Tau  | $0$      | 24.3 | 6                      | 45             | 3.13            | 14.8            | 17.7            |
| TW Hya    | $0$      | 18.2 | 24                     | 209            | 217             | 217             | 244             |

| $^a$ Velocity with respect to the star and FWHM are for narrow component only. |
| $^b$ Several blends from each star are counted as a single line. |
| $^c$ Observed flux, flux corrected for extinction, and model flux in 10$^{-14}$ ergs cm$^{-2}$ s$^{-1}$. |
| $^d$ Large aperture. |
| $^e$ Small aperture. |
| $^f$ Extinction to H$_2$ emission from DG Tau is very uncertain. |

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**Fig. 11.**—Spectral profiles of H$_2$ lines from upper levels ($v'$, $J'$) = (0, 1), (0, 2), and (2, 12) (solid lines), which are pumped on the red wing of Ly$\alpha$, compared with spectral profiles of H$_2$ emission from (1, 4) and (1, 7) (dotted lines), which are pumped near line center of Ly$\alpha$. The lines pumped near Ly$\alpha$ line center, from (1, 4) and (1, 7), in the T Tau and DF Tau spectra show excess blueshifted emission, relative to the flux in the narrow component, than is seen in lines from (0, 1), (0, 2), and (0, 12). The same lines from T Tau also show some excess redshifted emission. We do not detect any significant difference in emission line profiles for the different progressions in any other star, as illustrated here by RU Lupi.
is produced on-source. We cannot discriminate between a second point-source or continuous H$_2$ emission in the SW direction, but some of the remaining 30% of the emission must be extended by at least 70 mas from the star. The H$_2$ emission at $v = 50$ km s$^{-1}$ is not extended beyond the C IV emission (FWHM = 0''1).

Figure 15 shows the spatial extent of Ly$\alpha$ emission across the line profile (solid line), smoothed by 75 km s$^{-1}$, compared to the spatial extent of Si IV emission (dashed lines). Like the H$_2$ emission at $-15$ km s$^{-1}$, the Ly$\alpha$ emission is spatially extended SW of the star but not NE of the star. The spatial extent of the detected Ly$\alpha$ emission does not depend on the velocity. Even off source, the optical depth in the Ly$\alpha$ line is large enough to produce emission at $+800$ km s$^{-1}$ from line center.

5.2.3. T Tau

Figure 12 shows that the spatial profile of co-added H$_2$ emission from T Tau is slightly broader than the spatial profile of Si IV (top right) or C IV emission (bottom right). We co-add the H$_2$ lines from every upper level for this analysis to increase the S/N, even though the spectral profiles indicated that the lines pumped near line center of Ly$\alpha$ have stronger blueshifted emission than the other lines. The space-velocity diagram shown in Figure 16 indicates that the H$_2$ emission, particularly near $v = 0$ km s$^{-1}$, may be slightly more extended than the Si IV emission. The emission at $v = -50$ km s$^{-1}$ may be slightly less extended than Si IV emission. We caution, however, that the S/N in the space-velocity diagram is low and that any conclusions drawn from the diagram may therefore be suspect.

5.3. Wind Absorption of H$_2$ Lines

Two strong H$_2$ lines, 0–4 $R(0)$ and 0–4 $R(1)$ at 1333.5 and 1333.8 Å, respectively, are located at $-240$ and $-165$ km s$^{-1}$ from the C II 1334.5 Å resonance line. Those two H$_2$ lines may be attenuated by the stellar wind if the optical depth in this ground-state line is sufficiently large in the wind at those velocities.

Figure 17 shows the observed spectrum (shaded region) and model H$_2$ emission (dashed lines) for the 1333–1336 Å spectral region for the six stars in our survey. Table 12 describes the wind properties and the attenuation of the 0–4 $R(0)$ and 0–4 $R(1)$ lines.
We compare the maximum wind velocity ($v_w$) in the C II 1334.5 Å line with that from the Mg II 2796 Å line. We also compare the observed flux in the two H2 lines to the predicted flux, based on models described in § 4.2.

Herczeg et al. (2002) found that the 0–4 $R(1)$ 1333.8 Å line from TW Hya is weaker than expected from our models (see § 4.2) because the wind absorption in the C II line extends to $\sim -180$ km s$^{-1}$ in our line of sight. Both the 0–4 $R(0)$ and the 0–4 $R(1)$ lines from RU Lupi are attenuated by the optically thick wind, which extends to $\sim -240$ km s$^{-1}$. On the other hand, the observed flux in both lines from DF Tau is similar to the predicted flux, because the optically thick C II line in the wind of DF Tau only extends to $\sim -140$ km s$^{-1}$. Since the C II wind absorption from T Tau extends to $\sim -180$ km s$^{-1}$ and the H2 emission is shifted by $-12$ km s$^{-1}$, the optical depth of the wind at the 0–4 $R(1)$ 1333.8 Å line is small. We detect C II emission between 1333.5 and 1333.8 Å, so some of the emission at 1333.8 Å is likely from C II. Assuming the presence of some C II emission, we infer that the 0–4 $R(1)$ line in the T Tau spectrum is partially attenuated by the wind. The fluxes in both H2 lines from V836 Tau are similar to the model flux, although we would not expect any optically thick wind absorption at $165$ km s$^{-1}$ because the winds of WTTSs are not nearly as optically thick at large velocities as winds from CTTs. The 0–4 $R(1)$ line at 1333.8 Å appears weaker than expected from DG Tau, but the 0–5 $R(1)$ and 0–5 $R(2)$ lines at 1394 Å and the blend of 0–6 $R(1)$ and 0–6 $R(2)$ at 1455 Å are also much weaker than expected. Therefore, we cannot conclude that any H2 absorption is attenuated by the wind of DG Tau.

Several weaker H2 lines also overlap with wind absorption features. The 0–4 $R(3)$ line at 1335.1 Å, located at $-130$ km s$^{-1}$ from the C II 1335.7 Å line, may be detected from DF Tau but is not detected from TW Hya or RU Lupi because of wind absorption. We did not include this line from DF Tau in Table 5 because of the uncertain flux given the overlap with C II emission and low S/N. The red side of the 0–4 $R(3)$ line does not appear in the T Tau spectrum, which strengthens our inference that the on-source H2 emission from T Tau is attenuated by the wind. With better S/N than our data, several other lines are potentially useful for measuring attenuation of H2 emission by the wind, such as 3–2 $P(16)$ at 1305.663 Å located at $-84$ km s$^{-1}$ from the strong O I 1306 Å line.

These observations demonstrate that the H2 emission detected from TW Hya, RU Lupi, and T Tau is absorbed by the stellar wind. Based on the similar patterns of H2 emission, we infer that the H2 emission would also be absorbed by the winds of DF Tau, DG Tau, or V836 Tau if their winds were optically thick in C II at larger velocities. This attenuation suggests that the H2 emission is produced inside of any wind absorption, and as a result must be produced close to the central star.
5.4. Comparison to Previous Observations

Table 13 compares the fluxes, FWHM, and velocities of H$_2$ emission from DF Tau, RU Lupi, T Tau, and DG Tau in our HST STIS spectra and corresponding data obtained with HST GHRS of the same CTTSs, by Ardila et al. (2002a). The HST GHRS observations had $R = 20,000$, compared to $R = 25,000$–45,000 with STIS, and used a 2$''$ × 2$''$ aperture, compared to 0$''$.2 × 0$''$.06 and 0$''$.5 × 0$''$.5 with STIS. The absolute velocities are accurate to ±20 km s$^{-1}$ for pre-COSTAR GHRS spectra and to ±3 km s$^{-1}$ for STIS spectra. We compare H$_2$ lines pumped on the red side and near Ly$\alpha$ line center. Only a few line fluxes are co-added because the wavelength range of GHRS was limited to about 30 Å per exposure. We include the C iv flux as a rough proxy for the Ly$\alpha$ emission and mass accretion rate.

The centroid velocity of H$_2$ emission did not change significantly between the GHRS and STIS observations of RU Lupi, T Tau, and DF Tau. The FWHM of the H$_2$ emission from RU Lupi and T Tau is broader in the GHRS observation than in the STIS observation, which could be produced either by a real velocity dispersion or by spatially extended emission in the dispersion direction. The H$_2$ emission from the upper levels (1, 4) and (1, 7) from DG Tau, RU Lupi, and T Tau was much stronger relative to the C iv emission during the GHRS observation than during the STIS observation. Because of the larger aperture used for the GHRS observations than for the STIS observations, we infer that a reservoir of warm molecular gas extending beyond the star was present for RU Lupi, T Tau, and DG Tau.

The H$_2$ emission from DG Tau was more blueshifted in our STIS observation than in the GHRS observation, but the two observations could have sampled different gas. The GHRS observation of DG Tau exhibits strong C iv emission, which is not detected in our STIS spectra even though we would expect such emission based on the flux ratio of H$_2$ to C iv. The GHRS observations may have detected mostly extended emission in both H$_2$ and the other lines, including C iv. Güdel et al. (2005) detected extended X-ray emission from jets emanating from DG Tau. Hot gas traced by emission in C iv (Raymond et al. 1997) and possibly O vi (Herczeg et al. 2005) has previously been detected in outflows from CTTSs. However, Walter et al. (2003) and Saucedo et al. (2003) did not detect any extended C iv emission from T Tau, despite the presence of extended X-ray emission (Güdel et al. 2004). Takami et al. (2004) found near-IR H$_2$ emission in several lines from DG Tau, including the 1–0 S(1) transition, which is blueshifted by ~15 km s$^{-1}$ from the systemic velocity and offset from the source by 0$''$.2. They used relative H$_2$ line fluxes to estimate a temperature of 2000 K, which is hot enough to produce Ly$\alpha$-pumped H$_2$ emission in the FUV (e.g., Black & van Dishoeck 1987; Herczeg et al. 2004). Richter et al. (2002) estimated an upper flux limit of 3 × 10$^{-14}$ ergs cm$^{-2}$ s$^{-1}$ in the S(2) line at 12 µm from DG Tau.

Najita et al. (2003) detected fundamental CO emission from V836 Tau, but not from V410 Tau. Duvert et al. (2000) also detected weak CO J = 2–1 emission from V836 Tau. Bary et al. (2003) placed a flux upper limit of 9.4 × 10$^{-16}$ ergs cm$^{-2}$ s$^{-1}$ for the 1–0 S(1) line from V836 Tau. Our detection of H$_2$ emission from V836 Tau but not from V410 Tau is therefore consistent with previous studies, which suggested that V836 Tau retains gas in its disk but that V410 Tau retains neither a gas nor a dust disk.

6. DISCUSSION

Herczeg et al. (2002) found that the fluorescent H$_2$ emission from TW Hya is symmetric about the radial velocity of the star and is not spatially extended. They also found that the H$_2$ emission from TW Hya is attenuated by the wind, which constrains the origin of the emission to be close to the star. The only molecular gas known to be associated with TW Hya resides in its circumstellar disk. Therefore, the warm disk surface is a likely source for the H$_2$ fluorescence. However, the diverse spectral and spatial profiles of H$_2$ emission from other TTSs indicate that the source of H$_2$ emission depends on the target. Figure 2 shows no H$_2$ absorption against the observed Ly$\alpha$ emission from TW Hya, RU Lupi, or DF Tau. The Ly$\alpha$ emission from Mira B excites a similar pattern of H$_2$ fluorescence as seen here. Several H$_2$ absorption lines are detected against the Ly$\alpha$ emission because the H$_2$ is located in our line of sight to the Ly$\alpha$ emission source (Wood et al. 2002). Thus, the warm H$_2$ is not in our line of sight to TW Hya, RU Lupi, or DF Tau. We note that TW Hya, T Tau, and RU Lupi have disks that are most likely viewed face-on, whereas DF Tau and DG Tau have disks that are viewed edge-on. Table 14 summarizes stellar properties and the properties of the H$_2$ fluorescence for each source.

The H$_2$ emission from T Tau, RU Lupi, and DG Tau is blueshifted by 10–30 km s$^{-1}$, which indicates an outflow origin. The velocity of FUV H$_2$ emission from DG Tau is about 10 km s$^{-1}$ larger than that of the IR H$_2$ emission, which is offset by 0$''$.2 from the star and clearly associated with an outflow (Takami et al. 2004). The blueshifted H$_2$ emission from T Tau and RU Lupi extends to ~100 km s$^{-1}$ and is not spatially extended. Detecting H$_2$ at such high velocities is surprising because a strong shock should destroy the H$_2$, given its dissociation energy of 4.5 eV. When produced in an outflow, the H$_2$ emission appears blueshifted regardless of whether the disk is observed edge-on or face-on. The asymmetric blueshifted emission, however, extends to a much larger velocity for the face-on CTTS T Tau and RU Lupi than for the edge-on CTTS DF Tau. The absorption of H$_2$ emission by C ii in the wind restricts the H$_2$ to be produced interior to optically thick wind absorption. Therefore, the H$_2$ emission from these sources is likely produced at or near the base of the outflow.

Figure 18 shows the space-velocity diagram of H$\beta$ emission observed in our STIS G430L observation of RU Lupi. The blueshifted H$\beta$ emission is spatially extended symmetrically about the star, as we would expect for emission from a stellar wind, a disk wind from a face-on star, or possibly from the disk itself. The SW extent of the H$_2$ and Ly$\alpha$ emission suggests that they are instead produced by a jet, possibly sweeping up nearby molecular material. Takami et al. (2001) used spectro-astrometry...
of RU Lupi to find that blueshifted Hα emission is displaced by 20–30 mas to the SW of the star, and blueshifted [O i] and [S ii] emission is displaced by 30–300 mas to the SW of the star. Takami et al. (2001), however, also find redshifted Hα emission displaced by 30 km s\(^{-1}\) to the NE. Based on this detection, they infer that the edge-on disk of RU Lupi may have a central hole of 3–4 AU. This observational result is difficult to reconcile with the absence of either H2 or Lyα emission extended NE from the star and the absence of any extended redshifted Hβ emission.

Grady et al. (2005) found that the FUV emission from several CTTSs is extended by up to an arcsecond. This spatially extended emission may be produced either by extended H\(_2\) gas,
forward scattering by dust in a nearby nebulosity, or a jet interacting with nebulosity. In cases where only the H₂ emission from the CTTSs is extended, it is most likely related to the stellar outflows rather than the disk. The blueshifted H₂ emission may be produced where nearby nebulosity is shocked by outflows or in the dense outflows from CTTSs (e.g., Gomez de Castro & Verdugo 2001).

In their long-slit FUV spectra, Walter et al. (2003) and Saucedo et al. (2003) found that fluorescent H₂ emission is extended by at least 8'' from T Tau. This emission is most likely produced by the stellar outflows where they shock the surrounding molecular cloud. In the off-source spectrum, the only detected lines are from the stellar outflows where they shock the surrounding molecular gas. However, when log \( \nu \) (H I) > 14.5, the H I absorption at +14 km s\(^{-1}\) is optically thick. The Ly\( \alpha \) emission that excites (1, 7) must therefore be produced in situ. On the other hand, Walter et al. (2003) found in their long-slit spectra of DF Tau and T Tau. The Ly\( \alpha \) emission that irradiates this gas must be narrower than the Ly\( \alpha \) emission that irradiates the bulk of the on-source molecular gas and may be produced in the accretion shock. The narrow Ly\( \alpha \) emission associated with the outflow must also be produced close to the warm, blueshifted H₂ emission.

We do not detect any differences in the H₂ emission profiles from the various upper levels in the RU Lupi spectrum, even though the spatial extent of the H₂ and Ly\( \alpha \) emission implies that they are produced in the outflow. The outflow of RU Lupi is sufficiently optically thick that extended Ly\( \alpha \) emission is seen at +800 km s\(^{-1}\). In contrast, the absence of spatially extended Ly\( \alpha \) emission from TW Hya and DF Tau implies that the Ly\( \alpha \) emission from those two sources is most likely produced by the accreting gas. Because RU Lupi has a high mass accretion rate, the accretion flow may be optically thick to Ly\( \alpha \) emission, preventing us from detecting the Ly\( \alpha \) emission produced by the accreting gas. Stassun et al. (2004) speculate that X-ray emission of the Ly\( \alpha \) emission line that excites the on-source H₂ emission from T Tau must be broad and may be produced by accreting gas.

Like the extended emission from T Tau, we find excess blueshifted emission only in the lines from (1, 4) and (1, 7) in the on-source spectra of DF Tau and T Tau. The Ly\( \alpha \) emission that irradiates this gas must be narrower than the Ly\( \alpha \) emission that irradiates the bulk of the on-source molecular gas and may be produced in the accretion shock. The narrow Ly\( \alpha \) emission associated with the outflow must also be produced close to the warm, blueshifted H₂ emission.

### Table 12

| Star            | \( v_{\text{He}} \) (Mg ii 2796 Å) | \( v_{\text{Ne}} \) (C ii 1334.5 Å) | \( \nu_{\text{H}_2} \) | Model\(^a\) | Obs.\(^a\) | Model\(^a\) | Obs.\(^a\) |
|-----------------|------------------------------------|------------------------------------|--------------------------|-------------|------------|-------------|------------|
| DF Tau\(^b\)    | −190                               | −130                               | −1                       | 6.0         | 6.8        | 12.2        | 12.3       |
| TW Hya          | −205                               | −180                               | 0                        | 36.9        | 42.8       | 42.7        | 7.9        |
| RU Lupi         | −350\(^c\)                         | −240                               | −12                      | 4.7         | <2.1       | 6.1         | <0.2       |
| T Tau           | −300\(^c\)                         | −180                               | −12                      | 2.0         | <3.0       | 3.6         | <2.7       |
| DO Tau          | −330\(^c\)                         | ...                                | −27                      | 0.4         | 0.5        | 0.8         | ~0.4\(^b\) |
| V836 Tau        | ...                                | <−190\(^e\)                        | 0                        | 0.7         | 0.8        | 0.7         | 0.5        |

\(^a\) Flux, 10\(^{−15}\) ergs cm\(^−2\) s\(^−1\).
\(^b\) Obtained with large aperture.
\(^c\) From Ardila et al. (2002b).
\(^e\) Flux estimate unreliable.
\(^f\) Inferred from H₂ lines.

### Table 13

| STIS | GHRS\(^a\) |
|------|-------------|
|      |             |
| c     | c           |

| Star | \( v_{\text{He}} \) \(^b\) | FWHM\(^a\) | \( F_{\text{red}} \) \(^c,d\) | \( F_{\text{cen}} \) \(^c,e\) | \( F(\text{C iv}) \) \(^c\) | \( v_{\text{He}} \) \(^b\) | FWHM\(^a\) | \( F_{\text{red}} \) \(^c,d\) | \( F_{\text{cen}} \) \(^c,e\) | \( F(\text{C iv}) \) \(^c\) |
|------|----------------|-------------|-----------------|-----------------|----------------|----------------|-------------|----------------|-----------------|----------------|
| DF Tau\(^d\) | −1            | 23          | 46.3\(^e\)     | 5.8\(^b\)      | 330            | −1            | 27          | 52\(^e\)     | 4\(^b\)         | 498            |
| RU Lupi          | −12           | 18          | ...            | 14.9\(^b\)     | 700            | −17           | 37          | ...            | 26\(^b\)         | 146            |
| T Tau            | 28            | 16.1\(^b\)  | 12.8\(^b\)     | 230             | −9             | 52          | 33\(^b\)    | 98\(^b\)      | 166            |
| DG Tau           | −27           | 26          | 1.9\(^b\)      | 1.0\(^b\)       | <0.8           | −11           | 41          | 19\(^b\)     | 8\(^m\)         | 44             |

\(^a\) From Ardila et al. (2002a). DF Tau and RU Lupi were observed with GHRS before COSTAR was installed, leading to a ~20 km s\(^−1\) uncertainty in the absolute velocity scale. T Tau and DG Tau were observed after COSTAR was installed and have velocities measured to ~3 km s\(^−1\).

\(^b\) In units of km s\(^−1\).
\(^c\) Flux in various lines, in units of 10\(^{−15}\) ergs cm\(^−2\) s\(^−1\).
\(^d\) \( F_{\text{red}} \) lines from \((v', J') = (0, 1), (0, 2), \) and \((2, 12)\) pumped on the red wing of Ly\( \alpha \).
\(^e\) \( F_{\text{cen}} \) lines from \((v', J') = (1, 4)\) and \((1, 7)\) pumped near Ly\( \alpha \) line center.
\(^f\) Fluxes from observation obtained with 0.05'' aperture.
\(^g\) Co-added flux in 0–4 P(0), 0–5 P(2), 0–4 P(3), and 2–5 R(11) lines.
\(^h\) Flux in 1–8 P(5) line.
\(^i\) Flux in 1–8 R(6) and 1–8 R(5) lines.
\(^j\) Flux in 0–4 P(2), 0–5 P(2), 0–4 P(3), and 2–8 R(11) lines.
\(^k\) Flux in 1–7 R(3), 1–7 P(5), 1–8 P(5), 1–7 R(6), and 1–8 R(6).
\(^l\) Flux in 0–5 P(2), 2–5 R(11), and 2–8 R(11).
\(^m\) Flux in 1–8 R(3), 1–8 P(5), and 1–8 R(6).
from strongly accreting CTTSs may be similarly attenuated by accreting gas. The strong outflow that produces Lyα emission from RU Lupi may also produce the blueshifted O VI emission detected in FUSE spectra and could contribute to the complicated emission profiles of Si iv and C iv (Herczeg et al. 2005).

The bulk of the H2 emission from DF Tau and V836 Tau is consistent with a disk origin, because the H2 emission has the same radial velocity as the star and the bulk of the emission from DF Tau is not spatially extended. Our observations are unable to determine the spatial extent of H2 emission from V836 Tau. The weak blueshifted H2 emission from DF Tau is most likely associated with an outflow. The total H2 flux is not an appropriate indicator of the total amount of H2 present in circumstellar material, since the FUV H2 emission is produced only in warm (2000–3000 K) molecular gas that is irradiated by a strong FUV emission source and that has a large filling factor around that source.

Irradiated by strong Lyα emission, the hot disk surface of CTTSs can produce the observed H2 fluorescence. Therefore, it is surprising that very little if any H2 emission in the spectra of T Tau, RU Lupi, and DG Tau is produced at the stellar radial velocity, which suggests that fluorescent H2 emission is not produced at the surface of their disks. T Tau, RU Lupi, DG Tau, and DF Tau all have large mass accretion rates, while TW Hya has a small mass accretion rate. V836 Tau retains a disk and may be weakly accreting. Ardila et al. (2002a) found that the H2 emission is not blueshifted from BP Tau and RY Tau, both of which have moderate mass accretion rates, or from RW Aur, which has a high mass accretion rate. The H2 lines from the strongly accreting star DR Tau are blueshifted by 10 km s\(^{-1}\). Moreover, the velocity shift of the H2 emission does not appear to be correlated with dust settling or disk clearing, which is identified by the absence of excess NIR emission.

Mass-loss rates from CTTSs scale with mass accretion rates (Hartigan et al. 1995). The H2 emission from the strong accretors tend to be blueshifted and may be produced by outflows sweeping up molecular gas that either surrounds the star or is located at the disk surface, or at the base of the wind. Most of the Lyα emission is likely produced by the accreting gas, but it may also be produced or scattered by outflows. The absence of H2 emission from the disks of most of these strong accretors could result from the accretion flow being optically thick to the Lyα emission that is produced by the accreting gas.

Black & van Dishoeck (1987) calculated the FUV and IR H2 emission produced by Lyα pumping of H2. The FUV pumping of H2 can change the level populations and, as a result, modulate the emission in IR H2 lines. The models calculated by Black & van Dishoeck (1987) included a relatively narrow Lyα line because the IUE data from T Tau (Brown et al. 1981) and HH objects (Schwartz 1983) showed emission only in the H2 lines pumped near line center. Although their generic description of the H2 fluorescence from CTTSs is accurate, their specific results may not necessarily apply to the rich on-source H2 emission spectra described here. Nomura & Millar (2005) revisited the relationship between FUV pumping and IR H2 emission with a more realistic Lyα profile from TW Hya and a disk geometry to explain the emission in the strongest progressions. Their models predict H2 excitation temperatures that are too low to explain the emission in several other progressions, but may be sufficient...
with additional heating by X-rays. These investigations also demonstrate that emission in IR lines from warm H$_2$ gas depend on the FUV emission.

7. CONCLUSIONS

We have analyzed H$_2$ fluorescence in high-resolution HST STIS echelle spectra of the CTTSs TW Hya, RU Lupi, DF Tau, T Tau, DG Tau, and V836 Tau with the following results:

1. Between 41 and 209 H$_2$ lines are detected in each of these far-UV spectra. The H$_2$ emission is much brighter than that seen by the fluorescing H$_2$ gas around those stars. The strength of H$_2$ emission depends on the amount of warm (2000–3000 K) H$_2$ gas in the environment around the various stars, the strength of Ly$\alpha$ emission, and the solid angle filling factor of H$_2$ around the Ly$\alpha$ emission. This emission does not trace the bulk of the gas in the disk, which is cool.

2. The H$_2$ lines are pumped from many different levels, with the strongest lines typically pumped by five transitions located between 0 and 550 km s$^{-1}$ from Ly$\alpha$ line center. Several H$_2$ lines from all sources except T Tau are pumped by blueshifted Ly$\alpha$ emission, although those lines are weak in the spectra of DF Tau, RU Lupi, and V836 Tau. The H$_2$ lines from DF Tau and T Tau suggest that the Ly$\alpha$ emission irradiating the warm molecular gas around those stars is redshifted.

3. In the spectra of TW Hya and DF Tau, we find H$_2$ emission pumped by C IV from highly excited lower levels. This H$_2$ emission is consistent with ~3% of the warm gas having an excitation temperature of ~$2.5 \times 10^4$ K. The highly excited gas could be related to the strong FUV continuum detected from TW Hya and DF Tau. RU Lupi shows neither a strong FUV continuum nor these highly excited lines. Surprisingly, many highly excited H$_2$ lines that could be pumped by Ly$\alpha$ are not detected.

4. H$_2$ emission is detected from the WTTS V836 Tau, which contains a dust disk and is weakly accreting, but not from the WTTS V410 Tau, which no longer has a disk.

5. Walter et al. (2003) found that Ly$\alpha$ emission from T Tau is present in two G140L long-slit spectra but is absent in another long-slit spectrum and in the E140M echelle spectrum. We use the variability in H$_2$ lines from different upper levels to demonstrate that the width of the intrinsic Ly$\alpha$ profile changes, while the extinction and H I column density remain constant. We also find that the presence of H$_2$ emission pumped by the red wing of Ly$\alpha$ is correlated with Ly$\alpha$ emission at those wavelengths, even though our viewing angle is different from that seen by the fluorescing H$_2$ gas. We therefore conclude that the presence or absence of emission in the red wing of the Ly$\alpha$ emission profile is isotropic.

6. With the possible exception of DG Tau, the H$_2$ emission studied here must be produced close to the star because the bulk of the emission is not extended beyond a point source. The absorption of H$_2$ emission by C II in the wind requires that the H$_2$ emission is produced interior to the optically thick wind absorption. In cases where the Ly$\alpha$ is observed, the H$_2$ gas is not located in our line of sight to the Ly$\alpha$ emission region. The on-source H$_2$ fluorescence is excited by broad Ly$\alpha$ emission, in contrast to the spatially extended H$_2$ fluorescence detected from HH objects and the molecular complexes surrounding T Tau.

7. The H$_2$ lines show a diverse range of spatial and spectral profiles. The H$_2$ emission from RU Lupi, T Tau, and DG Tau is blueshifted, suggesting an outflow origin, while the emission from TW Hya, DF Tau, and V836 Tau is centered at the radial velocity of the star, suggesting a disk origin. The H$_2$ lines from DF Tau, RU Lupi, and T Tau include a weak blueshifted component.

8. In the spectra of T Tau and DF Tau, the H$_2$ lines from the (2, 1) upper levels, which are pumped near Ly$\alpha$ line center, have stronger excess blueshifted emission, relative to the flux in the narrow component, than the other H$_2$ lines pumped further from line center. The blueshifted component of these lines is likely produced in the outflow and may be pumped by Ly$\alpha$ emission produced in situ rather than in the accreting gas.

9. The H$_2$ and Ly$\alpha$ emission from RU Lupi are both extended to the SW relative to the emission in lines of C IV and Si IV, which are most likely produced by accreting gas. The H$_2$ and Ly$\alpha$ emission is presumably related to the blueshifted H$_2$, [O i], and [Si iv] emission also detected to the SW of the star by Takami et al. (2001). We speculate that the observed Ly$\alpha$ emission from RU Lupi, which pumps the H$_2$, may arise entirely in the outflow. The Ly$\alpha$ emission produced by the accreting gas could be absorbed by the accretion column.

10. Comparison of our STIS echelle spectra with the GHR observations suggests that H$_2$ emission from T Tau, RU Lupi, and DG Tau is also extended, particularly from the levels (1, 4) and (1, 7), which are pumped near Ly$\alpha$ line center. Extended H$_2$ is likely produced by outflows that shock the surrounding molecular material.

11. We do not find any stellar property that reliably predicts whether the H$_2$ emission will be produced in the warm disk surface or the outflow. The presence or absence of blueshifted H$_2$ emission does not appear to depend on disk evolution or environment. The absence of H$_2$ emission from a disk, however, tends to occur for the stars with higher mass accretion rates.

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