ABSTRACT

We report the first detection of molecular hydrogen (H\textsubscript{2}) absorption in the Ly\textalpha emission line profiles of two classical T Tauri stars (CTTSs), DF Tau and V4046 Sgr, observed by the Hubble Space Telescope Cosmic Origins Spectrograph. This absorption is the energy source for many of the Lyman-band H\textsubscript{2} fluorescent lines commonly seen in the far-ultraviolet spectra of CTTSs. We find that the absorbed energy in the H\textsubscript{2} pumping transitions from a portion of the Ly\textalpha line significantly differ from the amount of energy in the resulting fluorescent emission. By assuming additional absorption in the H\textalpha profile along our light of sight, we can correct the H\textsubscript{2} absorption/emission ratios so that they are close to unity. The required H\textalpha absorption for DF Tau is at a velocity close to the radial velocity of the star, consistent with H\textalpha absorption in the edge-on disk and interstellar medium. For V4046 Sgr, a nearly face-on system, the required absorption is between +100 km s\textsuperscript{-1} and +290 km s\textsuperscript{-1}, most likely resulting from H\textalpha gas in the accretion columns falling onto the star.

KEY WORDS: accretion, accretion disks – stars: individual (DF Tau, V4046 Sgr) – stars: pre-main sequence – ultraviolet: stars

1. INTRODUCTION

Molecular hydrogen (H\textsubscript{2}) emission lines are commonly observed in the far-ultraviolet (FUV) spectra of classical T Tauri stars (CTTSs; Herczeg et al. 2002, 2004, 2006; Ardila et al. 2002). Brown et al. (1981) first detected these lines from T Tau using the International Ultraviolet Explorer. As suggested by detections of identical lines in the sunspot spectrum (Jordan et al. 1977), these fluorescent H\textsubscript{2} lines are thought to be photoexcited from the ground electronic state to the B (or C) electronic state primarily by coincidence with hydrogen Ly\alpha, but also by other strong atomic emission lines (e.g., C II, C IV, and O VI) in the UV.

The H\textsubscript{2} fluorescence may arise from various locations in protostellar systems. In their analysis of the Hubble Space Telescope (HST) Space Telescope Imaging Spectrograph (STIS) E140M spectra of six pre-main-sequence stars, Herczeg et al. (2006) found that blueshifted H\textsubscript{2} lines of RU Lupi, T Tau, and DG Tau are likely formed in outflows, while the H\textsubscript{2} lines of TW Hya, DF Tau, and V836 Tau show no radial velocity shifts from the photospheric lines and are likely formed in warm (∼2500 K) surfaces of their circumstellar disks. Stars such as T Tau also show spatially extended H\textsubscript{2} fluorescent emission in associated nebulosity, which is likely pumped by local shocks and outflows rather than stellar Ly\alpha emission (Walter et al. 2003). For the diskless counterparts of CTTSs, the naked T Tauri stars (NTTSs), H\textsubscript{2} features are not seen in their FUV spectra (Ingleby et al. 2009; H. Yang et al. 2011, in preparation), indicating that H\textsubscript{2} fluorescent emission requires the presence of H\textsubscript{2} gas close to the central star. Studying the H\textsubscript{2} fluorescent emission therefore provides valuable information on the physical properties of protoplanetary disks, which are 90% composed of H\textsubscript{2} gas.

While the H\textsubscript{2} fluorescent lines have been studied in a number of CTTSs, the pumping transitions had not been observed in absorption against the Ly\alpha emission line. In this Letter, we present new FUV spectroscopy of two CTTSs, DF Tau and V4046 Sgr, for which we detect such absorption for the first time as a result of the very low noise and high throughput of the Cosmic Origins Spectrograph (COS) on HST.

2. OBSERVATIONS AND DATA REDUCTION

We observed DF Tau (R.A. = 04:27:02.795, decl. = 57:12:35.38) and V4046 Sgr (R.A. = 18:14:10.466, decl. = −32:47:34.50) with the COS (Dixon et al. 2010; Osterman et al. 2011) on 2010 January 11 and April 27, respectively. COS is a high-throughput, moderate-resolution UV spectrograph installed on the HST in 2009 May. During our HST GTO program 11533, we used both the G130M and G160M gratings of the COS FUV channel to cover the 1136–1796 Å region. Since there is a small gap (∼15 Å in wavelength coverage) between the two segments of the COS detector, we observed each star at four central wavelength settings for both gratings to provide continuous spectral coverage and minimize any fixed-pattern noise. The total exposure time for each star was about 10,000 s during four HST orbits. The spectral resolution was approximately 17,000–18,000, with extended wings in the line-spread function (LSF). The extended wings are induced by polishing errors on the HST primary and secondary mirrors (see Ghandi et al. 2010).

We reduced the DF Tau and V4046 Sgr spectra using the COS calibration pipeline, CALCOS (version 2.12, 2010 March 19), and combined them with a custom IDL co-addition routine described by Danforth et al. (2010). In Figure 1, we show two portions of the co-added FUV spectra for both stars as examples. To match the atomic and molecular emission lines with laboratory wavelengths, we corrected for the radial velocity

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5 We refer the reader to the Cycle 18 COS Instrument Handbook for more details: http://www.stsci.edu/hst/cos/documents/handbooks/current/cos_cover.html.
of DF Tau (15 km s\(^{-1}\)), but found that an additional correction of +8 km s\(^{-1}\) is needed because of inaccuracies in the CALCOS wavelength solution. The radial velocity of V4046 Sgr is close to 0, and the wavelength solution is accurate.

3. DF Tau AND V4046 Sgr

DF Tau is a binary system consisting of two early M stars separated by 0.1 \( \pm \) 0.01 (Schaefer et al. 2006). Its disk is inclined by 80°–85° (Johns-Krull & Valenti 2001; Ardila et al. 2002), i.e., the disk is seen nearly edge-on. The distance to DF Tau is generally adopted as 140 pc, the distance to the Taurus Molecular Cloud. Herczeg et al. (2006) analyzed in detail the H\(_2\) fluorescent lines of DF Tau observed with the STIS E140M grating. Herczeg & Hillenbrand (2008) estimated a visual extinction \((A_\text{V})\) of 0.6 mag and accretion rate in the range of \((2.3-4.6) \times 10^{-8} M_\odot\) yr\(^{-1}\) for DF Tau.

V4046 Sgr is a spectroscopic binary with a separation of 9 \( R_\odot\) and an orbital period of 2.42 days (Stempels & Gahm 2004). The pair consists of a K7V and a K5V star (Quast et al. 2000). At a distance of \(-72\) pc (Torres et al. 2008), it is an isolated system and the extinction is practically \( A_\text{V} = 0.0 \) mag (Stempels & Gahm 2004). The circumbinary disk is inclined at 35° (Quast et al. 2000; Kastner et al. 2008), somewhat face-on. V4046 Sgr may be a member of the \( \beta \) Pic Moving group and could be as old as 12 Myr (Ortega et al. 2002). Jensen & Mathieu (1997) found that it has little excess emission in the near-infrared (near-IR) wavelengths but a large excess emission at longer wavelengths, suggesting that optically thick dust in the regions of the disk close to the star has been cleared out. We know of no previous detailed study of H\(_2\) emission from V4046 Sgr.

Besides the H\(_2\) line emission studied in this work, the FUV continuum, which is also detected in DF Tau and V4046 Sgr, will be analyzed in detail by France et al. (2011).

4. ANALYSIS AND RESULTS

The FUV spectra of DF Tau and V4046 Sgr are dominated by H\(_2\) fluorescent lines (see Figure 1). Below 1200 Å, there are also many Werner-band H\(_2\) lines, which will be described in a separate paper (Yang et al. 2011, in preparation). In Figure 2, we show the Ly\(\alpha\) profiles of DF Tau and V4046 Sgr. The apparent absorption features seen against the Ly\(\alpha\) emission line have depths much greater than the noise at those wavelengths and coincide in wavelength with the Lyman-band H\(_2\) pumping transitions (see Table 3 of Herczeg et al. 2006). We first mask out the absorption features and fit fifth- or sixth-order polynomial curves to the Ly\(\alpha\) profiles. To measure the amounts of absorbed energy, we integrate the area between the fitted curves and the observed spectra. The uncertainties in such measurements are mainly caused by the somewhat subjective determinations of the Ly\(\alpha\) profiles without absorption. Some features result from the blended absorption of two or three pumping transitions, and the absorbed energy for these features represents the total absorption of the transitions. For DF Tau, five features are measured that correspond to nine pumping transitions: 1218.52 Å \(+1218.57\) Å, 1219.09 Å \(+1219.10\) Å \(+1219.15\) Å, 1219.37 Å \(+1219.48\) Å \(+1219.74\) Å, and 1220.18 Å. For V4046 Sgr, eight features are measured that correspond to 11 pumping transitions: 1212.43 Å \(+1212.54\) Å \(+1213.36\) Å \(+1213.68\) Å \(+1217.03\) Å \(+1217.04\) Å \(+1217.20\) Å \(+1217.41\) Å \(+1219.37\) Å \(+1219.48\) Å \(+1219.74\) Å, and 1220.18 Å. We detect between 2 and 19 fluorescent H\(_2\) lines in the progressions produced by each pumping transition observed in absorption against the Ly\(\alpha\) lines. The H\(_2\) fluorescent lines are identified based on the line list of Abgrall et al. (1993). To measure the line fluxes, we used a custom IDL fitting procedure (France et al. 2010) that convolutes a Gaussian profile with the COS LSF to fit the observed H\(_2\) line profiles. The convolutions of a Gaussian profile with the COS LSF only changes the shape of the profile but not the total line flux. The uncertainties in the line fluxes are generally less than 5% for unblended lines, indicative of the high signal-to-noise of the data, typically \(\gtrsim 50\) for the H\(_2\) lines. We next convert the line fluxes in each progression to the total energy emitted from the pumped upper level. Each H\(_2\) line in a given progression yields an estimate of the total energy in the upper level from the line theoretical branching ratios.

![Figure 1](image1.png)
We average the estimated total energy emitted from each upper level using only the strong unblended lines, and their standard deviations are \(\leq 15\%\) of the mean values. The emission from each upper level is corrected for its dissociation probability as calculated by Abgrall et al. (2000). The dissociation probability is typically zero or only a few percent. The absorption and emission fluxes for DF Tau are also corrected for extinction using \(A_V = 0.6\) mag and the Cardelli et al. (1989) extinction law.

For each absorption feature observed against the Ly\(\alpha\) emission line, we have estimated the absorbed energy (\(E_{\text{abs}}\)) and the emitted energy (\(E_{\text{em}}\)) from the corresponding H\(_2\) upper level. If there are no additional sources of absorption or emission, then the global average of \(E_{\text{abs}}/E_{\text{em}}\) should be unity. We begin the analysis by assuming that \(E_{\text{abs}}/E_{\text{em}}\) along our line of sight should be close to unity, but the measurements show otherwise. We do find that the three features in the Ly\(\alpha\) blue wing for V4046 Sgr have \(E_{\text{abs}}/E_{\text{em}}\) within a factor of two of unity (1.38, 0.99, 0.56), but the \(E_{\text{abs}}/E_{\text{em}}\) ratios at longer wavelengths are smaller than one by factors of 4–60 (see the fourth column of Table 1). We therefore propose that additional Ly\(\alpha\) absorption in the line of sight between the location where H\(_2\) is pumped and the observer has reduced the observed absorbed energy in the pumping line and thus the \(E_{\text{abs}}/E_{\text{em}}\) ratios. To model the additional hydrogen absorption, we calculate Ly\(\alpha\) absorption profiles using the Voigt function for a range of hydrogen column densities (\(N_{\text{H}_2}\)) and radial velocities (\(v_{\text{rad}}\)). Then for each combination of \(N_{\text{H}_2}\) and \(v_{\text{rad}}\), we calculate the optical depths, \(\tau(\lambda)\), at the wavelengths of the pumping lines. We correct the observed \(E_{\text{abs}}/E_{\text{em}}\) ratios by multiplying by \(e^{-\tau(\lambda)}\). For V4046 Sgr, the absorption features at 1217.03 Å and 1217.20 Å are not used. The 1217.03 Å feature is close to the line center of Ly\(\alpha\), and the measurement is greatly affected by the absorption in the line center. The 1217.20 Å progression does not have enough strong unblended emission lines to provide an accurate estimate of the emission energy.

In Figure 3, we show for DF Tau and V4046 Sgr the combinations of \(N_{\text{H}_2}\) and \(v_{\text{rad}}\) that can correct the \(E_{\text{abs}}/E_{\text{em}}\) ratios to be close to unity. For DF Tau, if we assume that the extinction is all due to interstellar dust, we can convert \(A_V = 0.6\) mag to a total hydrogen column density of \(\log(N_{\text{H}_2}) = 21.03\) according to the relation in Predehl & Schmitt (1995). Note that this value assumes a standard gas-to-dust ratio for the interstellar medium. We mark in the top panel of Figure 3 the corresponding \(N_{\text{H}_2}\) values assuming 100% and 50% neutral hydrogen. Herczeg et al. (2006) estimated for DF Tau the absorption against the red wing of the Ly\(\alpha\) emission line and measured a \(\log(N_{\text{H}_2})\) of 20.75. This value is close to the hydrogen column density converted from \(A_V\) with 50% neutral content and represents the neutral hydrogen in both the interstellar medium along the line.

![Figure 2. Ly\(\alpha\) emission profiles of DF Tau (top panel) and V4046 Sgr (bottom panel). The red dashed lines indicate the uncertainty levels, and the vertical ticks mark the wavelengths of coincident Lyman-band H\(_2\) transitions. The blue areas indicate our estimates of the absorption in the H\(_2\) pumping transitions. In the bottom panel, the emission bump centered around 1215.7 Å is geocoronal emission and is not from the star.](image-url)
of sight and possibly the edge-on disk of the system. As shown in Figure 3, within reasonable ranges of \( N_{\text{HI}} \), the additional absorption required to bring all of the \( E_{\text{abs}}/E_{\text{em}} \) ratios close to unity for DF Tau requires radial velocities close to zero. Given that the uncertainty in \( A_V \) could be as large as 0.4 mag, and the ionization fraction and the gas-to-dust ratio in the disk are unknown, we think that the absorption is likely caused by a combination of interstellar medium and neutral hydrogen in the edge-on disk, though absorption by the H I columns in stellar winds or accretion columns cannot be completely ruled out.

For V4046 Sgr, which suffers negligible continuum extinction, the absorption required has a radial velocity between 100 and 290 km s\(^{-1}\), as shown in the bottom panel of Figure 3. If \( A_V \) is close to zero (Stempels & Gahm 2004), then the radial velocity is close to 290 km s\(^{-1}\). For this case, we list in Table 1 the calculated optical depth for the additional absorption as well as the measured and corrected \( E_{\text{abs}}/E_{\text{em}} \) for the absorption features detected in V4046 Sgr. This is consistent with a scenario in which H I in the accretion columns is absorbing the red wings of the Ly\( \alpha \) emission line in this system, which is oriented somewhat face-on.

5. DISCUSSION

Thanks to the excellent sensitivity and low background of COS, we were able to detect for the first time H\(_2\) absorption against the Ly\( \alpha \) emission line profiles in two CTTSs. Because of the large aperture of COS (2.5'), the center of the Ly\( \alpha \) line is filled with geocoronal Ly\( \alpha \) emission and not usable (see Figure 1). The STIS E140M spectrum of DF Tau reported by Herczeg et al. (2006) shows that the line center and blue wing of Ly\( \alpha \) are completely absorbed. Interstellar absorption must be responsible for the disappearance of the line center, because we see many H\(_2\) lines pumped by transitions coincident with the center of Ly\( \alpha \). On the other hand, we detect only a few H\(_2\) lines pumped by the transitions blueward of line center, suggesting that the blue-wing emission of Ly\( \alpha \) has been absorbed by the stellar wind before the blue-wing radiation reaches the molecular gas in the disk. Since the disk of DF Tau is viewed nearly edge-on, the stellar wind must be present near the stellar equator to absorb the blue wing of the Ly\( \alpha \) emission line.

Understanding the geometry of the V4046 Sgr system requires more detailed consideration. The stellar wind must be weak for this somewhat face-on system since the blue wing of Ly\( \alpha \) is not totally absorbed. Our results show that there is additional absorption in the red wing of Ly\( \alpha \) that could be explained by accretion with velocities that are at least 100 km s\(^{-1}\) and are likely as large as 290 km s\(^{-1}\). We envision a model in which a portion of the Ly\( \alpha \) emission, likely formed near the accretion shocks, is reflected to the observer by neutral hydrogen in the inner disk. A schematic of this model is shown in Figure 4. The H\(_2\) pumping and fluorescence occur where these Ly\( \alpha \) photons are present in the inner disk, as described by the “thick disk” model in Herczeg et al. (2004). The reflected Ly\( \alpha \) emission line, including the H\(_2\) absorption at the pumping wavelengths, is then absorbed by infalling neutral hydrogen in large accretion funnels in our line of sight.

Figure 3. H\(_2\) absorption/emission ratios of DF Tau (top panel) and V4046 Sgr (bottom panel), corrected for additional Ly\( \alpha \) absorption for a range of H I column densities and radial velocities.

Figure 4. Schematic of the V4046 Sgr system, which is not drawn to scale. The blue wavy arrows represent stellar and reflected Ly\( \alpha \) photons, and the red wavy arrows represent the fluorescent H\(_2\) photons. The dust disk begins at 0.18 AU from the star, according to Jensen & Mathieu (1997). The short black arrows indicate the flow direction along the accretion funnels. The long black and gray arrows point to our line of sight, which is at \( \sim 35\degree \) with respect to the rotation axis of the disk. The long black arrow indicates that there is more reflected light from the inner edge of the gas disk that faces toward our line of sight than that from the opposite side, which is indicated by the long gray arrow, because of absorption through the disk along this line of sight.
Accretion of gas from circumstellar disks onto CTTSs is generally thought to be controlled by stellar magnetic fields (Bouvier et al. 2007). Strong magnetic fields of a few kilogauss (Johns-Krull 2007; Yang & Johns-Krull 2011) truncate the circumstellar gas disk at a few stellar radii and direct the accretion funnels onto the star near the magnetic poles. From models of the spectral energy distribution of V4046 Sgr, Jensen & Mathieu (1997) found that dust in the inner regions is cleared out to about 0.18 AU, which is 38.6 $R_\odot$. At this distance, the stellar magnetic fields are not strong enough to interact efficiently with the disk, and, more importantly, the temperature of molecular gas at the surface of the dusty disk may not be high enough for the hydrogen molecules to be electronically excited by the Ly$\alpha$ photons. For this transitional disk system, we think that both the fluorescent emission and accretion columns likely originate from the inner molecular gas disk (Muzerolle et al. 2003; Kastner et al. 2008) that is closer to the central star than the dust disk. The absence of any significant differences between the radial velocities of the star, pumping lines, and fluorescent lines is consistent with the fluorescent H$_2$ gas lying in an inner gas disk seen nearly face-on. In this picture as shown in Figure 4, we expect to see more reflected light from the inner edge of the “thick disk” (cf. Figure 8 in Herczeg et al. 2004) facing toward both stars will show absorption mostly by downflowing neutral hydrogen (seen along the long black line in Figure 4) rather than upflowing neutral hydrogen (seen along the long gray line in Figure 4).

Günther & Schmitt (2007) modeled the accretion shocks on V4046 Sgr, and their best-fit model of the X-ray observations yields an accretion rate of $3 \times 10^{-11} M_\odot$ yr$^{-1}$ and a maximum infall velocity of 535 km s$^{-1}$ where the accretion gas strikes the stellar surface. Since the H $\alpha$ absorption velocity is between +100 and +290 km s$^{-1}$, the absorbing H $\alpha$ gas is located between 2.3 $R_*$ and 4.4 $R_*$ above the accretion shock (cf. Equation (1) in Calvet & Gullbring 1998) if we assume that the accretion columns have a constant cross-sectional area and the infalling gas sees only gravitational forces.

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