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Observational constraints on disk photoevaporation by the central star

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Abstract. We apply results from FUV and X-ray spectroscopy to evaluate the role of photoevaporation in dispersing the disk around TW Hya. Accretion produces bright EUV emission that may be smothered by the accretion column. Solar-like magnetic activity produces fewer ionizing photons, which may be absorbed by an accretion-powered neutral wind. We estimate a photoevaporation rate of $\sim 5 \times 10^{-11}$ $M_{\odot}$ yr^{-1} for the disk around TW Hya. These models can be tested by detecting gas in the ionized disk surface, including emission in the [Ne II] 12.8μm line. Photoevaporation is likely a minor process in disk dispersal during the accretion phase, but could remove ~ 1 M_J of remnant gas around a solar-mass star after accretion ceases.

Keywords. Stars: planetary systems: protoplanetary disks, stars: pre–main-sequence, accretion, stars: coronae

1. Introduction

Photoevaporation by EUV (< 912 Å) emission from the central star has been proposed as a dominant mechanism in disk dispersal (see review by Dullemond *et al.* 2007). In the detailed photoevaporation models of Alexander *et al.* (2006ab), ionizing radiation from the central star can heat the disk surface to $\sim 10^4$ K, leading to evaporation between 1–10 AU. If strong enough, solar-like magnetic activity could supply sufficient ionizing radiation to sustain photoevaporation rates of 10^{-10} to 10^{-9} M$_{\odot}$yr^{-1}, even as the accretion ceases.

Photoevaporation models require estimates for the ionizing flux incident upon the disk. However, the EUV emission from the central star is undetectable because of H absorption in our line of sight. Instead, the EUV radiation field at the disk surface can be estimated by calculating the flux from the star and correcting for any attenuation by neutral gas between the star and the disk. Alexander *et al.* (2005) estimated a ionizing photon flux of $10^{41} - 10^{44}$ phot s^{-1} from CTTSs based on the C IV λ1549 line luminosity. They assumed that the C IV emission is chromospheric and that all of the EUV emission from the star reaches the disk. Alternately, observational probes of the ionized disk surface could constrain the ionizing radiation incident upon the disk.

In this proceedings, we apply X-ray and FUV observations of the nearby classical T Tauri star (CTTS) TW Hya to evaluate photoevaporation models. TW Hya is an older CTTS with a mass accretion rate about an order of magnitude lower than that of younger Taurus CTTSs. The IR spectral energy distribution and imaging at 7mm indicates that the inner disk within 4 AU of the star is cleared of optically-thick dust (Calvet *et al.* 2002; Hughes et al. 2007), although gas and optically-thin micron-sized dust grains remain (Herczeg *et al.* 2002; Eisner *et al.* 2006). Such disk clearing may result from photoevaporation, the presence of a giant planet, or grain growth (Dullemond & Dominik 2005; Alexander *et al.* 2006b; Najita et al. 2007). TW Hya is therefore an ideal CTTS to determine whether photoevaporation is significant in disk dispersal.

Since hot lines in FUV and X-ray spectra of TW Hya are attributed to accretion, we

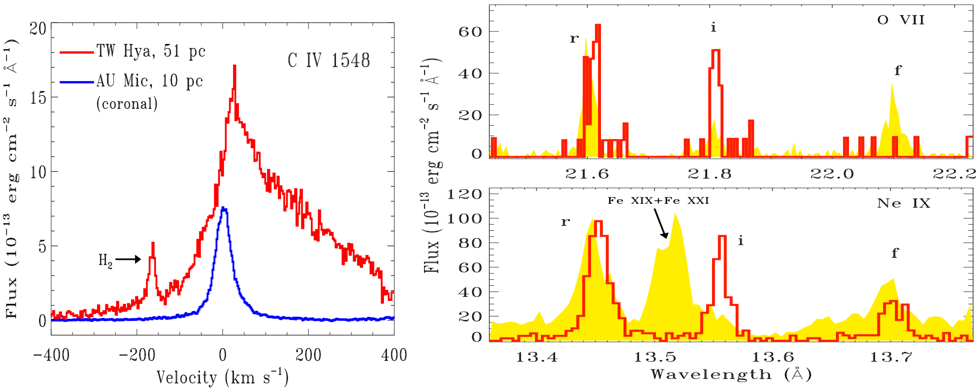

Figure 1. Left: Adapted from Johns-Krull & Herczeg (2007). The C IV emission from TW Hya (d=51 pc) is dominated by a broad red wing. In contrast, C IV emission from AU Mic (d=10 pc) is produced in the transition region, is centered at the stellocentric velocity, and is 200 times less luminous than that from TW Hya. **Right:** Adapted from Kastner *et al.* (2002). The forbidden line of He-like triplets from TW Hya is suppressed relative to coronal sources (Capella shown here in yellow), either due to densities of $\sim 10^{12.5}$ cm^{-3} or a strong FUV radiation field. Either explanation requires that the O VII and Ne IX lines are produced at or near the accretion shock.

suggest that the large estimate for EUV emission from TW Hya also applies to accretion. These photons may be smothered by the accretion column. Any photoevaporation of the disk around TW Hya may instead be dominated by the smaller amount of ionizing radiation produced by solar-like magnetic activity. We find that the amount of ionizing radiation is 1-3 orders of magnitude lower than that estimated by Alexander *et al.* 2005, and suggest that photoevaporation may not be significant until accretion ceases.

2. EUV irradiation of the disk

The amount of ionizing radiation that reaches the disk depends on the intrinsic ionizing luminosity from the star and attenuation of those photons by any neutral or molecular gas between the emission region and the disk. Ionizing photons can be produced by the accretion shock, which reaches temperatures of $\sim 10^6$ K (Calvet & Gullbring 1998), the 10^4 K accretion-heated stellar photosphere (e.g., Valenti *et al.* 1993), the transition region between a solar-like corona and chromosphere, or accretion-powered stellar outflows.

Alexander *et al.* (2004) found that the accretion column will attenuate any emission produced in the 10^4 K accretion continuum, since such emission occurs very close to the Lyman limit. In contrast, ionizing radiation produced by the accretion shock will be dominated by line emission and dispersed across a broad wavelength region. Such emission may be able to escape the accretion column. In the following subsections, we calculate the EUV luminosity from the accretion flow and from solar-like magnetic activity.

2.1. *The EUV luminosity of the accretion column*

Alexander *et al.* (2005) used line emissivities and the luminosity of C IV $\lambda1549$ doublet to estimate the ionizing radiation from CTTSs. Johns-Krull & Herczeg (2007) found that the asymmetric C III, C IV, N V, and O VI lines from TW Hya have a redshifted centroid and a broad wing that extends to ~ 400 km s^{-1}, consistent with formation in the accretion flow (Fig. 1a). Likewise, high-resolution X-ray spectra of TW Hya (Kastner *et al.* 2002; Stelzer & Schmitt 2004) show that the forbidden-to-intercombination line ratio of the

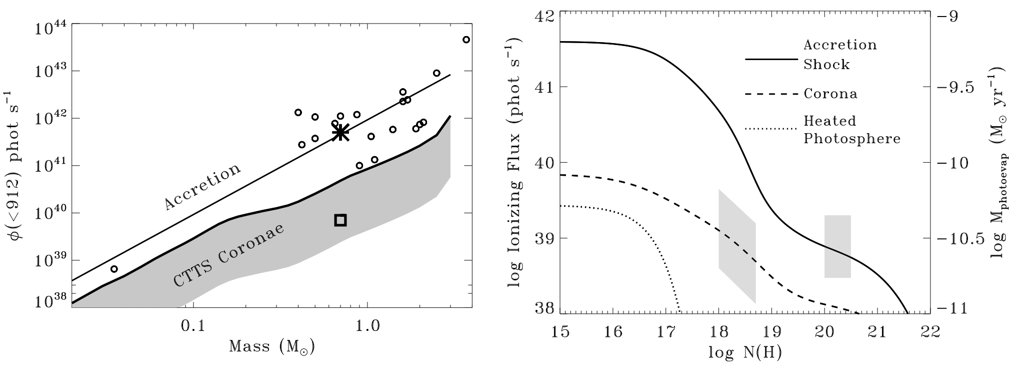

Figure 2. Left: The approximate ionizing photon fluxes from CTTSs, based on C IV luminosity in *HST*/STIS FUV spectra (circles, with TW Hya as the asterisk), correlates with stellar mass and mass accretion rate. The ionizing radiation from magnetic activity (shaded region with TW Hya, square) is much less, even if the X-ray emission is saturated (solid line). **Right:** The number of ionizing photons from the star, adjusted for any N(H I) between the emission region and the disk. The shaded regions show estimates for the ionizing radiation that reaches the disk.

O VII and Ne IX He-like triplets is suppressed (Fig. 1b), which requires that the soft X-ray emission is produced at or near the accretion shock. Therefore, calculating EUV line emission from FUV or X-ray line fluxes from TW Hya provides an estimate for the ionizing radiation produced by the accreting gas.

We calculate a differential emission measure (DEM) and abundances for TW Hya from X-ray and FUV line fluxes (Kastner *et al.* 2002; Stelzer & Schmitt 2004; Herczeg et al. 2004) and *CHIANTI* line emissivities (Dere *et al.* 1997), assuming collisional ionization equilibrium. We then use the DEM to calculate line fluxes for EUV lines.

We estimate an ionizing photon flux from the accretion shock on TW Hya of $\sim 5 \times 10^{41}$ phot s^{-1} (Fig. 2a). Ardila (this volume) describes that collisional ionization may be a poor assumption for the accretion flow. Similarly, some uncertainty in relative abundances of C, N, O, Ne, and He, including a large relative Ne abundance, also adds to the uncertainty. However, since our estimates for EUV fluxes are tied to observed FUV and X-ray fluxes, we estimate an uncertainty of ~ 5 for this estimate for the ionizing photon flux.

2.2. *Estimating the EUV luminosity from the transition region*

Figure 1a shows that the C IV luminosity produced by the transition region of the 12 Myr old AU Mic is 200 times less than the total C IV luminosity from TW Hya. C IV emission from the transition region of TW Hya and most other CTTSs is masked by accretion onto the star. The coronal X-ray luminosity from TW Hya is also somewhat uncertain because of confusion with X-ray emission produced by accretion. Therefore, the total ionizing emission produced by solar-like magnetic activity on TW Hya is poorly constrained.

The differential emission measure for AU Mic was calculated by del Zanna *et al.* (2002) and is used here as a rough template for CTTSs. The emissivity at 10^5 K varies as $L_X^{0.5}$, based on an analysis of older coronal source by Ayres (1997). The shaded region of Figure 2a shows the estimated range of EUV flux from solar-like magnetic activity on TTSs as a function of mass. We calculate the approximate upper limit for EUV photon flux by assuming saturated X-ray emission ($L_X/L_{bol} = 10^{-3}$) for 1 Myr-old pre-main sequence tracks from D'Antona & Mazzitelli (1994). WTTSs are often saturated in X-rays, while X-ray emission from CTTSs is typically three times weaker (Preibisch *et al.* 2005).

If we assume that $\sim 10\%$ of X-ray emission from TW Hya is coronal ($\log L_X/L_{bol} = -3.7$), then the total ionizing photon flux will be $\sim 7 \times 10^{39}$ phot s^{-1} (Fig. 2).

3. Is X-ray emission from the accretion shock smothered?

Gahm (1980) and Walter & Kuhi (1981) first suggested that X-ray emission from CTTSs may be smothered based on differences in X-ray luminosity between WTTSs and CTTSs in early *EINSTEIN* observations. This idea was largely abandoned when the IR excess from CTTSs was attributed to circumstellar disks rather than envelopes. However, if some X-ray emission is produced by the accretion shock, then it may be buried beneath neutral gas in the accretion column (e.g., Calvet & Gullbring 1998; Drake 2005).

The N(H I) to CTTSs can be measured from either Lyman continuum absorption in X-ray spectra or from line absorption in FUV spectra. Figure 3 shows H I absorption from *HST*/STIS FUV and *FUSE* FUV spectra of TW Hya (Herczeg *et al.* 2004; Johns-Krull & Herczeg 2007). Lyα and Lyβ absorption lines are seen against emission in the same lines. Several absorption lines, including Lyδ and other lines not shown here, are seen against weak continuum emission. H Lyman absorption lines near 923 Å are detected, presumably against emission in the N IV multiplet.

The lack of any polarimetric signature in Hα emission from TW Hya (Yang *et al.* 2007) suggests that Hα emission, and therefore perhaps other H lines, are produced in a heated photosphere distributed on the star. Any difference in N(H I) between the two methods may be attributed to N(H I) between X-ray and Lyman line emission.

The absorption includes an interstellar component centered at -13 km s^{-1} and a wind component centered at -130 km s^{-1}, based on spectrally-resolved absorption components in O I, C II, and Mg II lines. We fit the absorption lines with Voigt profiles to measure N(H I). The optically-thick absorption in the *FUSE* lines extends to -280 km s^{-1}. If the N(H I) is the same to all FUV emission, such absorption requires that the Doppler broadening parameter is ~ 50 km s^{-1}. Based on the Lyα line, we find that N(H I)$= 10^{19}$ cm^{-2} in the interstellar medium (Herczeg *et al.* 2004) and 3×10^{19} cm^{-2} in the wind, for a total N(H I)$=4 \pm 1 \times 10^{19}$ cm^{-2}.

These estimates assume that the H I scatters the Lyα photons out of our line of sight. The blueshifted absorption is not consistent with a self-reversed profile. However, the wind may be local to the star, in which case the Lyα photons will not scatter out of our line of sight. By modelling local scattering in a pure-hydrogen slab, we find that the N(H I) measured from a simple Voigt profile may be underestimated by $\sim 1.5 \times 10^{19}$ cm^{-2}.

Therefore, we estimate that N(H I)$=6 \times 10^{19}$ cm^{-2} to the Lyα emission region. Herczeg *et al.* (2004) also measured $N(H_2) < 10^{18}$ cm^{-2} from the non-detection of H_2 absorption lines in a *FUSE* spectrum of TW Hya. The N(H I) to the X-ray emission from TW Hya was measured to be $5.2 \pm 3.7 \times 10^{20}$ cm^{-2} in a *ROSAT* spectrum (Kastner *et al.* 1999) and $3.5 \pm 0.5 \times 10^{20}$ cm^{-2} in an *XMM* spectrum (Robrade & Schmitt 2006). Figure 3a shows that the Lyα absorption profile for such a large N(H I) is inconsistent with the observed absorption.

X-ray and FUV measurements of N(H I) are discrepant by $\sim 3 \times 10^{20}$ cm^{-2}. These measurements may be explained if N(H I) lies between the stellar photosphere and to the X-ray-emitting gas, or by invoking variability. We note that N(H I) measured from *ROSAT* and *XMM* observations of TW Hya, obtained years apart, are similar.

The N(H I) of 1.5×10^{21} cm^{-2} and 3.1×10^{21} cm^{-2} measured from the *XMM* spectra of the CTTSs BP Tau and SU Aur by Robrade & Schmitt (2006) are also much larger than the N(H I) of 5×10^{19} cm^{-2} and 5×10^{20} cm^{-2}, respectively, measured from Lyα absorption by Lamzin (2006). These N(H I) measurements have a larger uncertainty

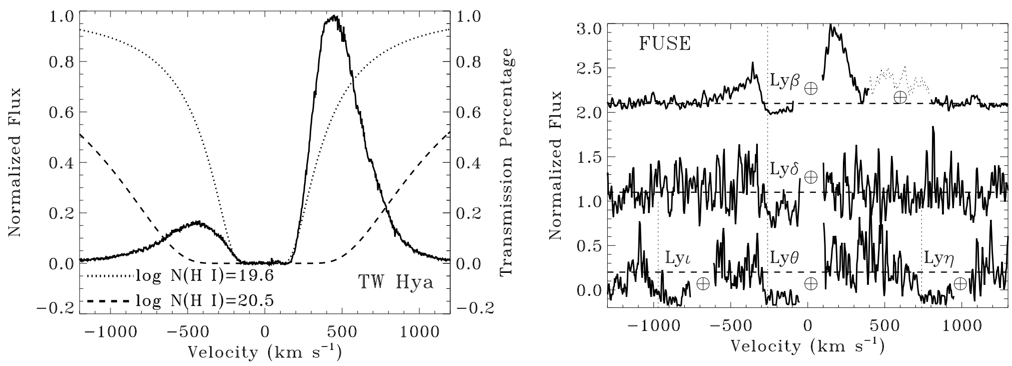

Figure 3. H I absorption in our line of sight to TW Hya can be measured using absorption lines in *HST*/STIS FUV spectra (**left**, adapted from Herczeg *et al.* 2004) and in *FUSE* spectra (**right**, top panel adapted from Johns-Krull & Herczeg 2007). The H I absorption includes a wind component at -130 km s^{-1} and an interstellar component at -13 km s^{-1}. The left panel shows the observed emission (solid line) compared with the transmission percentage for N(H I)$= 4 \times 10^{19}$ (dotted line) and 3×10^{20} cm^{-2} (dashed line). The N(H I) in our line of sight to the Lyα emission from TW Hya is less than the N(H I)$= 3.5 \times 10^{20}$ measured by Robrade & Schmitt (2006) from Lyman continuum absorption in an *XMM* spectrum of TW Hya.

than for TW Hya because they are measured from spectra with low resolution and lack complementary *FUSE* spectra, which means that $N(H_2)$ cannot be measured. However, the molecular fraction in our line of sight would have to be $\sim 95\%$ and 80%, respectively, to explain the discrepant N(H I) measurements from the FUV and X-ray spectra of BP Tau and SU Aur.

The difference in N(H I) measurements for BP Tau and SU Aur are much larger than that for TW Hya, possibly the result of larger mass accretion rates for the former two stars. At present we can only compare N(H I) measurements from FUV and X-ray spectra for those three stars, which have both STIS and *XMM* spectra. Strong outflows may corrupt similar N(H I) measurements from the Lyα line profile seen from RU Lup and T Tau.

4. Estimating photoevaporation rates

Hollenbach *et al.* (1994) estimate a photoevaporation mass loss rate of $3 \times 10^{-10} \left(\frac{\phi}{10^{41}\mathrm{phot}}\right)^{0.5}$ $M_\odot$ yr^{-1} for a 0.6 $M_\odot$ star, where ϕ is the flux of ionizing photons from the central star. Alexander *et al.* (2005) estimate an ionizing flux of $10^{41} - 10^{44}$ phot s^{-1} from CTTSs. However, if this emission from accretion is buried under $\sim 3 \times 10^{20}$ cm^{-2} of neutral gas, then the ionizing photons from the accretion shock that reach the disk are $\sim 10^{39}$ phot s^{-1}.

The neutral wind will also attenuate some EUV emission. Ardila *et al.* (2002) found that a low-temperature wind was present for all CTTSs, regardless of inclination. In an analysis of FUV H_2 emission, Herczeg *et al.* (2004) detected neutral gas between the Lyα emission region and the warm H_2 in the disk (Figure 4a). This gas is blueshifted in the frame of the H_2 with a N(H I)$\lesssim 5 \times 10^{18}$ cm^{-2}. Although only an upper limit because of uncertain Doppler broadening, such gas will attenuate any EUV emission from both the accretion and from the transition region.

Combining the ionizing photon flux from both sources (Figure 2), we estimate a photoevaporation mass loss rate of $\sim 5 \times 10^{-11}$ $M_\odot$ yr^{-1}. Even if the accretion-related EUV emission is not buried in the accretion column, neutral gas in the wind will likely constrain the photoevaporation rate to $< 3 \times 10^{-10}$ $M_\odot$ yr^{-1}. However, with a much larger mass accretion rate onto TW Hya of 10^{-9} to 10^{-8} $M_\odot$ yr^{-1} (as estimated from optical veiling by Alencar & Batalha 2002 and from excess UV emission by Herczeg *et al.* 2002), viscous dissipation likely dominates.

As with TW Hya, the photoevaporative mass loss rate for other stars depends on the EUV emission produced by accreting gas and the N(H I) in the accretion column. FUV observations of CTTSs indicate that C IV luminosity, which serves as a proxy for the EUV luminosity, correlates with accretion rate (Johns-Krull *et al.* 2000; Calvet *et al.* 2004) but may not always arise at or near the accretion shock (see review by Ardila, this volume). For example, C IV emission from DG Tau and RY Tau is blueshifted and therefore likely produced at or near the base of the outflow, while C IV emission from some other stars is seen at the radial velocity of the star.

For these stars with larger mass accretion rates, the ionizing flux may reach as high as 10^{43} phot s^{-1}, leading to a photoevaporation rate of 5×10^{-9} $M_\odot$ yr^{-1}. However, these stars also have stronger neutral outflows (Hartigan *et al.* 1995), which can attenuate much of the ionizing radiation before it irradiates the disk. The photoevaporation rate most likely stays below the rate of viscous dissipation for such stars.

Accreting low-mass stars and brown dwarfs have much smaller accretion rates than solar-mass CTTSs (e.g., Muzerolle *et al.* 2005). Based on the small C IV luminosity detected from the brown dwarf 2MASS1207-3932 (Gizis et al. 2005), the total EUV emission from the accretion shock will be much smaller for these stars. If the N(H I) in the accretion column is sufficiently small because the mass accretion rate is also small, then enough ionizing radiation may escape to lead to a photoevaporation rate of $\sim 10^{-11}$ $M_\odot$ yr^{-1}.

Once accretion ceases, any wind disappears and the photoevaporative rate due to solar-like magnetic activity may be as high as $\sim 3 \times 10^{-10}$ $M_\odot$ yr^{-1} for a solar-mass star. Thus, while photoevaporation might be negligible throughout the accretion process, as much as $\sim 3M_J$ of remnant gas could be dispersed over 10 Myr by photoevaporation after accretion ceases. This low photoevaporation rate requires one of the following possibilities: 1) long survival timescales for gas in disks after accretion ceases, which has not been seen (e.g., Roberge *et al.* 2005; Pascucci *et al.* 2006); 2) other disk dispersal mechanisms more efficient than photoevaporation, such as wind-disk interactions; or 3) accretion continues until < 1 M_J of gas is removed from the disk.

5. A direct probe of disk ionization

The results described above provide only indirect estimates of disk irradiation and suffer from substantial uncertainties. A probe of the ionized disk surface is needed test these estimates. Recently, Pascucci *et al.* (2007) and Lahuis *et al.* (2007) may have found such a probe by detecting emission in the [Ne II] 12.81μm fine-structure line in low-resolution *Spitzer* IRS spectra of CTTSs. [Ne II] was detected in four of six targets in the Pascucci *et al.* (2007) sample and in 15 of 76 targets in the Lahuis *et al.* (2007) sample. Lahuis *et al.* (2007) also detected [Ne III] emission from one source (Sz102).

We used MICHELLE on Gemini North to detect bright [Ne II] emission from TW Hya with $R \sim 30,000$ (Fig. 4b). This emission is located at the stellar radial velocity and has an intrinsic FWHM of 21 ± 4 km s^{-1}, which confirms speculation that the line is produced in the disk. The line width is broader than other narrow emission lines typically associated with the disk around TW Hya. If formed in a disk, the line broadening could result from turbulence in a warm disk atmosphere, Keplerian rotation at an average distance of 0.1

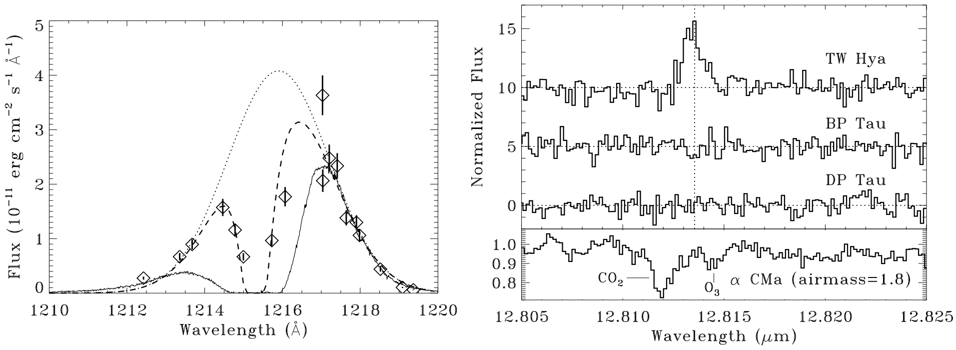

Figure 4. Left: Herczeg *et al.* (2004) reconstruct the Lyα emission incident upon H_2 gas in the disk (diamonds), compared to the observed Lyα profile (thick solid line). H I located between the star and disk, with a velocity of ~ -90 km s^{-1} from line center, absorbs some Lyα emission. **Right:** Strong [Ne II] emission in high-resolution Gemini North/MICHELLE spectra of TW Hya, with a dotted line indicating the stellocentric velocity for each source.

AU from the star, or a photoevaporative flow from the optically-thin region of the disk. Additional high-resolution spectra can discriminate between these scenarios.

Two ionization paths can ionize Ne and thereby produce the [Ne II] emission. Glassgold *et al.* (2007) propose that the line is formed because of Ne ionization by K-shell absorption of stellar X-rays at energies > 0.9 keV. The observed [Ne II] fluxes and the [Ne III]/[Ne II] flux ratio and lower limits are consistent with predictions from this X-ray ionization model. Alternately, EUV photons shortward of the Ne I ionization edge at 575 Å can produce [Ne II] emission if the EUV emission is able to penetrate through neutral gas in the accretion column and wind. Combining X-ray and EUV ionization models should provide estimates for the total EUV flux incident upon the disk surface.

6. Discussion

We find evidence that the EUV and soft X-ray emission from TW Hya may be smothered. The accretion column could attenuate most ionizing radiation produced by the accretion shock. We estimate photoevaporation rates of $\sim 5 \times 10^{-11}$ $M_\odot$ yr^{-1} from ionizing radiation produced by both the accretion shock and by solar-like magnetic activity.

The difference in N(H I) measurements need to be verified to ensure that the result is not attributable to variability. The results are also dependent on geometry, if the N(H I) of the accretion column is larger when seen face-on than when seen edge-on, as the disk views a dipolar accretion flow. Observations and modelling of [Ne II] emission will help to verify estimates of ionizing radiation incident upon the disk.

These results suggest that mass loss from disk photoevaporation is much smaller than viscous dissipation until accretion slows to undetectable rates. Alexander *et al.* (2006b) and Najita et al. (2007) both suggest that disk photoevaporation may be significant for CoKu Tau/4, which has a large inner disk hole and no previously identified accretion signatures. However, photoevaporation can only be a significant process if the timescale for gas dissipation is > 10 Myr or accretion leaves $\lesssim 1 M_J$ of gas in the disk.

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References

Alexander, R.D., Clarke, C.J., Pringle, J.E. 2004, MNRAS, 354, 71
Alexander, R.D, Clarke, C.J., & Pringle, J.E. 2005, MNRAS, 358, 283
Alexander, R.D, Clarke, C.J., & Pringle, J.E. 2006a, MNRAS, 369, 216
Alexander, R.D, Clarke, C.J., & Pringle, J.E. 2006b, MNRAS, 369, 229
Alencar, S.H.P., & Batalha, C. 2002, ApJ, 571, 378
Ardila, D.R., Basri, G., Walter, F.M., Valenti, J.A., & Johns-Krull, C.M. 2002, ApJ, 567, 1013
Ayres, T.R. 1997, JGR, 102, 1641
Calvet, N., & Gullbring, E. 1998, ApJ, 509, 802
Calvet, N., D'Alessio, P., Hartmann, L., *et al.* 2002, ApJ, 568, 1008
Calvet, N., Muzerolle, J., Briceno, C., *et al.* 2004, AJ, 128, 1294
D'Antona, F., & Mazzitelli, I. 1994, ApJS, 90, 467
del Zanna, G., Landini, M., & Mason, H.E. 2002, A&A, 385, 968
Dere, K.P., *et al.* 1997, A&AS, 125, 149
Drake, J.J. 2005, Proceedings of *13th Cool Stars Workshop*, eds. F. Favata, G. Hussein, & B. Battrick. 519
Dullemond, C.P., Hollenbach, D., Kamp, I., D'Alessio, P. 2007, proceedings of *P&PV*, eds. B. Reipurth, D. Jewitt, and K. Keil, 951, 555
Dullemond, C.P., & Dominik, C. 2005, A&A, 434, 971
Eisner, J.A., Chiang, E.I., & Hillenbrand, L.A. 2006, ApJ, 637, L133
Gahm, G.F. 1980, ApJ, 242, L163
Gizis, J.E., Shipman, H.L., Harvin, J.A. 2005, ApJ, 630, L89
Glassgold, A.E., Najita, J.R., & Igea, J. 2007, ApJ, 656, 515
Hartigan, P., Edwards, S., Ghandour, L. 1995, ApJ, 452, 736
Herczeg, G. J., Linsky, J. L., Valenti, J.A., Johns-Krull, C.M. 2002, ApJ, 572, 310
Herczeg, G.J., *et al.* 2004, ApJ, 607, 369
Hollenbach, D., Johnstone, D., Lizano, S., & Shu, F. 1994, ApJ, 428, 654
Hughes, A.M., *et al.* 2007, ApJ, accepted. astro-ph:0704.2422
Johns-Krull, C.M., Valenti, J.A., & Linksy, J.L. 2000, ApJ, 539, 815
Johns-Krull, C.M., & Herczeg, G.J. 2007, ApJ, 655, 345
Kastner, J.H., Huenemoerder, D.P., Schulz, N.S., & Weintraub, D.A. 1999, ApJ, 525, 837
Kastner, J. H. Huenemoerder, D. P., Schulz, N. S., *et al.* 2002, ApJ, 567, 434
Lahuis, F., van Dischoeck, E.F., Blake, G.A., *et al.* 2007, ApJ, accepted. astro-ph/07042305
Lamzin, S.A. 2006, AstL, 32, L176
Muzerolle, J., Luhman, K.L., Briceno, C., Hartmann, L., & Calvet, N. 2005, ApJ, 620, L107
Najita, J., Carr, J.S., Glassgold, A.E., & Valenti, J.A. 2007, PPV
Pascucci, I., *et al.* 2006, ApJ, 651, 1177
Pascucci, I., *et al.* 2007, ApJ, 663, 383
Preibisch, T., *et al.* 2005, ApJS, 160, 582
Roberge, A., Weinberger, A.J., & Malumuth, E.M. 2005, ApJ, 622, 1171
Robrade, J., Schmitt, J.H.M.M. 2006, A&A, 449, 737
Stelzer, B., Schmitt, J.H.H.M. 2004, A&A, 418, 687
Walter, F.M. & Kuhi, L.V. 1981, ApJ, 250, 254
Valenti, J.A., Basri, G., & Johns, C.M. 1993, ApJ, 106, 2024
Yang, H., Johns-Krull, C.M., & Valenti, J.A. 2007, AJ, 133, 73