A HOT WIND FROM THE CLASSICAL T TAURI STARS: TW HYDRAE AND T TAU
A. K. DUPREE,1,2,3 N. S. BRICKHOUSE,1,3 GRAEHE H. SMITH,4 AND JAY STRADER5
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ABSTRACT

Spectroscopy of the infrared \( \text{He}^+ \) (10830 Å) line with NIRSPEC on Keck and CSHELL at the IRTF, and of the ultraviolet \( \text{C}^3 \) (977 Å) and \( \text{O}^3 \) (1032 Å) emission with \textit{FUSE}, reveals that the classical T Tauri star TW Hydrae exhibits P Cygni profiles, line asymmetries, and absorption indicative of a continuous, fast (\( \sim 400 \text{ km s}^{-1} \)), hot (\( \sim 300,000 \text{ K} \)) accelerating outflow with a mass-loss rate \( \sim 10^{-11} \) to \( 10^{-12} M_{\odot} \text{ yr}^{-1} \) or larger. Spectra of T Tau N appear consistent with such a wind. The source of the emission and outflow seems restricted to the stars themselves. Although the mass accretion rate is an order of magnitude less for TW Hya than for T Tau, the outflow reaches higher velocities at chromospheric temperatures in TW Hya. Winds from young stellar objects may be substantially hotter and faster than previously thought.

Subject headings: infrared: stars — stars: individual (TW Hydrae, T Tauri) — stars: pre–main-sequence — stars: winds, outflows — ultraviolet: stars

1. INTRODUCTION

Young stars with accretion disks display energetic jets observed in optical transitions from low stages of ionization—\( \text{[O ii]}, \text{[Fe ii]}, \text{[S ii]}, \text{[N i]}, \text{[N ii]} \)—as well as molecular outflows. The source of these outflows is not well determined. Shu et al. (1994) argued that they arise from the truncation region of the accretion disk, where the stellar magnetosphere, frozen into the disk, causes super-Keplerian rotation and drives a magneto-centrifugally accelerated wind. Königl & Pudritz (2000) suggest an extended region of the accretion disk itself may be responsible. Or, several regions may contribute to a cool wind, as indicated by \([\text{Fe ii}]\): the disk forming a wide-angle low-velocity component, whereas a high-velocity component is launched from a region next to the truncation radius (Pyo et al. 2003). In addition, near-UV and optical lines show signs of outflow apparently from the photosphere and low chromosphere (Ardisa et al. 2002; Herczeg et al. 2002). To date, the dynamics and energetics of the outflows in young stars have been principally constrained by these low-temperature species, and the modeled winds are generally cool, \( T < 10^4 \text{ K} \) (Shang et al. 2002). Beristain et al. (2001) detected broad wings in \( \text{He}^+ \) 5876 and suggested that this signaled a warmer wind. It is important to determine the physical properties of these winds and identify their source, for they can affect angular momentum loss, disk structure, and acceleration of optical jets.

Additional unique spectral features can provide diagnostics of the dynamics of outflows from young stars and are reported here. Two transitions are particularly valuable: One is the chromospheric \( \text{He}^+ \) line (\( \lambda=10830 \text{ Å} \); \( 2s^2S \rightarrow 2p^3 P \)) arising from a metastable state predominantly populated by recombinations following photoionization by the extreme-UV continuum. In a cool luminous star, this transition is generally formed higher in the atmosphere (\( T \sim 20,000 \text{ K} \)) than \( \text{He}^+ \) and the \( \text{Ca}^+ \) and \( \text{Mg}^+ \) emission cores (Dupree et al. 1992). Because \( \lambda=10830 \text{ Å} \) is not coupled to local conditions, it is useful to indicate bulk motions in cool stars, including a handful of young stellar objects (Dupree et al. 1992; Edwards et al. 2003; Takami et al. 2002; Dupree 2004). Importantly, this \( \text{He}^+ \) line is unaffected by interstellar or circumstellar absorption. Another valuable diagnostic is the resonance line of \( \text{C} iii \) (\( \lambda=977 \text{ Å} \)), which has the highest opacity of any of the major UV resonance transitions. Judged by atomic physics, the opacity of \( \text{C} iii \) at \( \lambda=977 \text{ Å} \) exceeds all other major far-UV resonance lines by factors of 3–10 (Dupree et al. 2005), making it sensitive to absorption that could reveal the presence of a wind. In a collisionally ionized plasma, \( \text{C} iii \) signals temperatures of \( \sim 80,000 \text{ K} \) (Young et al. 2003). Effects of mass motions causing asymmetries in UV line profiles are widely observed in luminous cool stars (Dupree & Brickhouse 1998; Carpenter et al. 1999; Dupree et al. 2005), and the interpretation of asymmetries in relation to atmospheric dynamics is confirmed from semiempirical modeling (Lobel & Dupree 2001).

Two well-studied classical T Tauri stars are good targets. TW Hydrae and T Tauri have rotation axes oriented with low inclinations, less than 20° and between 8° and 13°, respectively (Krist et al. 2000; Herbst et al. 1986), so that the stellar polar regions are observed directly. The accretion disks are observed face-on. Although the dipole component of the stellar magnetic field, where disk material is thought to be channeled to the star and thermalized in an accretion shock (Hartmann 1998 and references therein), may not be aligned with the rotation axis of the star, it is still in view. TW Hya is older (10 Myr) than T Tau, and the accretion rate may be low (\( \sim 4 \times 10^{-10} M_{\odot} \text{ yr}^{-1} \) from \( \text{H} \alpha \) [Muzerolle et al. 2000], \( 10^{-8} \) to \( 10^{-9} M_{\odot} \text{ yr}^{-1} \) from Na D [Alencar & Batalha 2002]), whereas T Tau N (7.3 Myr) has a much higher accretion rate of (3.1–5.7) \( \times 10^{-9} M_{\odot} \text{ yr}^{-1} \) (Calvet et al. 2004; Johns-Krull et al. 2000). Since mass outflows are thought to be proportional to the mass accretion rate (Calvet 2004), different winds might be expected from these two stars.

2. OBSERVATIONS

TW Hydrae was observed at \( \lambda=10830 \text{ Å} \) in 2002 July at Keck II using the NIRSPEC instrument (McLean et al. 1998). Observations were made using the echelle cross-dispersed mode with the NIRSPEC-1 order-sorting filter and a slit of 0′43 × 12′′, yielding a nominal resolving power of 23,600.
Fringing was minimized by not using the two PK 50 blocking glass filters. The exposure time totaled 480 s. The spectrum was reduced using the REDSPEC IDL software package. The wavelength scale was established using NeArKr arc lamps and set to photospheric values using the Si i and Mg i absorption as reference. He i λ10830 in T Tau was observed at the IRTF with CHSEL (Greene et al. 1993) in 1992 August. A 1" slit was used; the instrumental resolution is 15 km s⁻¹ and the exposure time was 10 minutes. This spectrum shows residual fringing near −400 km s⁻¹. Standard IRAF procedures were used to reduce the spectra. The wavelength scale, determined by Ar and Kr lamps, is set to the photospheric value using the Si i absorption at 10844.02 Å. Figures 1 and 2 show that both stars have He i P Cygni profiles. The absorption extent reaches −280 km s⁻¹ in TW Hya and −220 km s⁻¹ in T Tau. Since the He i line is formed at chromospheric temperatures, these velocities are supersonic and may be an indication of shocks and transient events. The photospheric escape velocity is ∼500 km s⁻¹ for these stars, but at a distance of 1 R* above the surface, the escape speed approaches 300 km s⁻¹, so a small extension of the atmosphere could easily lead to mass loss.

FUSE spectra (Moos et al. 2000) of TW Hya (Fig. 1), obtained from MAST, have a total exposure time of 30.6 ks. Exposure set C0670101 (15.9 ks) was centered at JD 2,452,690.834; exposure set C0670102 (14.7 ks) was taken 1 day later. We use the total exposure. Segments of the SiC2A (containing λ977) and LiF1A (containing λ1032) exposures were examined to ensure that the channel alignment was in place; segment 1 of C0670102 was discarded because of the short exposure time. Extractions of night-only observations were made using CALFUSE 2.4 to verify that scattered solar light is absent in the day spectra. Individual segments were cross-correlated using stellar emission lines and summed for SiC2A (containing λ977) and LiF1A (containing λ1032). The wavelength offsets are determined using interstellar absorption features in the spectrum. For TW Hya, interstellar absorption of O i, C ii, Si ii, and Mg ii occurs at a heliocentric velocity of 0 ± 3 km s⁻¹ (Herczeg et al. 2004), and the interstellar absorption in C iii λ977 has been set to that velocity with an uncertainty of about ±5 km s⁻¹. The radial velocity
of TW Hya is taken as $+12.5 \text{ km s}^{-1}$ (Alencar & Batalha 2002). The wavelength offset for the LiF1A channel was adopted from the CALFUSE reduction. Since that channel is used for FUSE guiding, the offset is the most reliable; the observed wavelengths of the airglow lines are equal to their rest values within a few kilometers per second, giving support to this offset. The uncertainty in this procedure is about $\pm 10 \text{ km s}^{-1}$. Far-UV spectra of T Tau N were obtained from the FUSE archive (P1630101), where reduction procedures similar to those described above were followed. The shortest exposure segments were deleted from 14 data segments, to achieve a total exposure of 19.5 ks. Interstellar lines observed in Mg II at $+8 \text{ km s}^{-1}$ (Aréllaga et al. 2002) set the SiC2A scale by matching to the interstellar C III absorption. The radial velocity of T Tau is taken as $+17.5 \text{ km s}^{-1}$.

3. EVIDENCE FOR HOT WINDS

The profile of C III $\lambda 977$ in TW Hya exhibits P Cygni structure with a clear absorption trough recovering near $-325 \text{ km s}^{-1}$ and extending to higher outflow velocities than the He I line. As expected (Hummer & Rybicki 1968; Lobel & Dupree 2001), a self-absorbed line in a differentially expanding atmosphere appears asymmetric, with a steeper slope occurring on the negative-velocity side than on the positive-velocity side of the profile. A similar shape is found in the O vi line, although no diminution of absorption creating an emission "bump" is detected. Since cool stars lack a local continuum in this part of the far-UV spectrum, the line intensity drops to near zero, exactly what is observed in C III and O vi. The similarity of the profile shapes in TW Hya suggests that the wind at the C III level (80,000 K) continues to higher temperatures of $3 \times 10^4$ K (Young et al. 2003), indicated by the presence of O vi asymmetry, assuming a collisionally ionized plasma. The C IV and N v profiles of TW Hya (Herczeg et al. 2002) also show the same asymmetry as O vi, typical of wind absorption.

The presence of wind opacity can be investigated by fitting a Gaussian profile to the long-wavelength wing of the UV lines in TW Hya (Fig. 1). These one-sided fits predict line centers of $-13 \pm 5$ and $+3 \pm 9 \text{ km s}^{-1}$ for C III and O vi, respectively, and have similar FWHM (C III, 1.04 $\pm 0.02$ Å; O vi, 1.14 $\pm 0.04$ Å). The difference between the observed profile and the fit reveals the wind absorption. In Figure 3, the profiles are normalized to the local continuum provided by the Gaussian fit. The furthest outward extent of the profile reaches $-260 \text{ km s}^{-1}$ for He I, $-325 \text{ km s}^{-1}$ for C III, and $-440 \text{ km s}^{-1}$ for O vi. These values are in harmony with the velocity of cooler material, inferred from Hubble Space Telescope STIS spectra to be $-230 \text{ km s}^{-1}$ from lines of O I, C II, and N I (Herczeg et al. 2002), suggesting the accelerating outflow is typical of a stellar wind. Solar wind models (Hu et al. 2000) demonstrate that ions possess different speeds depending on mass, charge, and wind-heating characteristics.

A rough estimate of the mass-loss rate required to produce the absorption profiles in Figure 3 can be derived from the Sobolev optical depth, assuming $\tau_0 = 1$ (Hartmann 1998). For an outflow velocity of 400 km s$^{-1}$ (the total width of the O vi absorption), reached over a distance of $R_*$, and a solar oxygen abundance ($\text{O/H} = 8.5 \times 10^{-4}$) with maximum fractional ionization for O vi of 0.2, the mass-loss rate follows as $M_{\text{O vi}}/\phi = 2.3 \times 10^{-11} M_\odot \text{ yr}^{-1}$, where $\phi$ is the fraction of the surface where the wind originates. Similarly for C III, an acceleration to 300 km s$^{-1}$ over $R_*$ suggests $M_{\text{C III}}/\phi = 1.3 \times 10^{-12} M_\odot \text{ yr}^{-1}$, taking C/H = 3.6 $\times 10^{-12}$ and a fractional ionization of 0.8. A wind from high-latitude regions might have $\phi \sim 0.3$. These values are less than the accretion rate inferred from $\dot{M}$, $4 \times 10^{-10} M_\odot \text{ yr}^{-1}$ (Muzerolle et al. 2000). However, if wind optical depths are much larger, possibly $10^3$ (Hartmann 1998), the mass-loss rate becomes comparable to the accretion rate.

The far-UV spectrum of T Tau is clearly of lesser quality than that of TW Hya, but characteristics of the profiles are similar to TW Hya: namely, a P Cygni He I line extending to $-220 \text{ km s}^{-1}$, a C III width less than O vi, and profiles consistent with blue asymmetry. In T Tau, the far-UV lines are narrower than the He I emission, which, in a wind model, would suggest absorption with a higher column density than in TW Hya.

4. DISCUSSION AND CONCLUSIONS

It is difficult to determine the source of the UV line emission that provides the flux for wind scattering, but it must be close to the star. Dwarf stars show strong emission from C III and O vi (Redfield et al. 2002) associated with activity, and we expect a similar contribution here. UV line fluxes generally increase in T Tauri stars that are undergoing accretion, suggesting an origin in the accretion disk, X-region, or the shocked accretion column. The accretion disks in both sources contain H$_2$, are dusty, and thus are unlikely to create and support plasma at $10^5$ K. The intersection of the dipole magnetic field from the star and the accretion disk, perhaps the source of the X-wind, is also unlikely to be responsible, as it is thought to be ionized and heated by X-rays only to temperatures of $\sim 10^4 K$ or less (Shang et al. 2002). Part of the UV emission undoubtedly results from the accretion shock. Profiles of emission from highly ionized ions in an accretion shock have not been reliably calculated; the emission observed might arise either from turbulent broadening associated with the shocked, cooling gas or from infalling gas from the near-side accretion stream. Nonthermal broadening could produce intrinsically symmetric profiles as modeled here. On the other hand, emission from the infalling gas on the far side might be blocked by the star, producing an intrinsically asymmetric profile. The emission at $-320 \text{ km s}^{-1}$ in the C III line seems to rule out this second case, as we would expect similar features from C iv, N v, and O vi. Furthermore, the star would preferentially block the high-
est velocities, not the lowest velocities, since the accretion stream accelerates toward the stellar surface.

T Tauri stars are frequently associated with optical jets and Herbig-Haro (H-H) objects. Because our targets are face-on, jets along the line of sight might contribute emission from high-temperature material. However, high-excitation H-H objects that contain C iv also exhibit a UV continuum (Böhm et al. 1987) that is absent here. One of the brightest H-H objects in the sky shows neither C iii nor O vi in a Hopkins Ultraviolet Telescope spectrum (Raymond et al. 1997). FUSE spectra of HH 1 and HH 2, obtained from MAST, also give no signs of these ions. Thus, it is not likely that H-H objects contribute to the emission reported here.

The emission components of C iii and O vi are exceptionally broad. Both T Tau and TW Hya are slow rotators (v sin i of 20.9 and 5 ± 2 km s⁻¹, respectively; Hartmann et al. 1986; Alencar & Batalha 2002), yet the observed emission line widths exceed those values (C iii, 102 and 202 km s⁻¹; O vi, 140 and 219 km s⁻¹, respectively). Accounting for absorption can nearly double the intrinsic widths. If the emission is attributed to active regions, the broadening would represent an extreme example of the weak broadening found in normal stars (Redfield et al. 2002). Emission associated with the accretion flow and shock is likely to show turbulent broadening. We note that the UV line widths are significantly larger than the X-ray line widths. If the X-rays from TW Hya are generated at the accretion shock (Kastner et al. 2002), the UV lines may not be directly associated with the shock. On the other hand, studies of X-ray emission in young star clusters suggest that the strength of the X-ray emission is correlated with stellar rotation, thus casting doubt on an accretion origin for the X-rays (Stassun et al. 2004).

Whatever the source of these collisionally excited photons, originating on or close to the star, they appear to be scattered in the outflowing plasma, producing a sequence of similar P Cygni profiles ranging from He i and C iii to O vi. In our interpretation, the wind signatures indicate a continuous outward acceleration from approximately the photospheric velocity to several hundred kilometers per second and reach temperatures of 3 × 10⁵ K. A cool wind has been suggested in TW Hya (Herczeg et al. 2002, 2004) as a component in the complex Lyα profile, and also from the weakness of one H₂ line possibly affected by C ii absorption. Other H₂ transitions subject to wind absorption may offer insight into the configuration of the stellar wind if the site of the fluoresced H₂ can be identified. A high-temperature, fast wind might contribute to the opacity needed (Stassun et al. 2004) for the absorption of X-rays in accreting systems. In addition, a fast hot wind may influence the diminution of dust in accretion disks (Alexander et al. 2005).

Detailed semiempirical modeling will be necessary to derive meaningful mass-loss rates. The velocities observed in TW Hya are larger than in T Tau, although the wind may be less opaque, which is surprising if wind characteristics are related to the accretion rate.

The profiles reported here are consistent with the presence of hot winds reaching escape velocities, which may lead to shocks and optical jets as the wind decelerates at greater distances from the star. The polar orientation of TW Hya and T Tau enables full access to regions likely to contain open field lines enhancing mass outflow. Observations of disk-star systems at various inclination angles can help to define the structure of both the emission region and the wind.

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REFERENCES

Alencar, S. H. P., & Batalha, C. 2002, ApJ, 571, 378
Alexander, R. D., Clarke, C. J., & Pringle, J. E. 2005, MNRAS, 358, 283
Ardila, D. R., Basri, G., Walter, F. M., Valenti, J. A., & Johns-Krull, C. M. 2002, ApJ, 567, 1013
Biferisti, G., Edwards, S., & Kwan, J. 2001, ApJ, 551, 1023
Böhm, K.-H., Bührke, T., Raga, A. C., Brugel, E. W., Witt, A. N., & Mundt, R. 1987, ApJ, 316, 349
Calvet, N. 2004, in IAU Symp. 219, Stars as Suns, ed A. K. Dupree & A. O. Benz (San Francisco: ASP), 599
Calvet, N., Muzerolle, J., Briceño, C., Hernández, J., Hartmann, L., Saucedo, J. L., & Gordon, K. D. 2004, AJ, 128, 1294
Carpenter, K. G., Robinson, R. D., Harper, G. M., Bennett, P. D., Brown, A., & Mullan, D. I. 1999, ApJ, 521, 382
Dupree, A. K. 2004, in IAU Symp. 219, Stars as Suns, ed A. K. Dupree & A. O. Benz (San Francisco: ASP), 623
Dupree, A. K., & Brickhouse, N. S. 1998, ApJ, 500, L33
Dupree, A. K., Lobel, A., Young, P. R., Ake, T. B., Linsky, J. L., & Redfield, S. 2005, ApJ, 622, 629
Dupree, A. K., Sasselov, D. D., & Lester, J. B. 1992, ApJ, 387, L85
Edwards, S., Fischer, W., Kwan, J., Hillenbrand, L., & Dupree, A. K. 2003, ApJ, 599, L41
Greene, T. P., Tokunaga, A. T., Toomey, D. W., & Carr, J. S. 1993, Proc. SPIE, 1946, 313
Hartmann, L. 1998, Accretion Processes in Star Formation (Cambridge: Cambridge Univ. Press)
Hartmann, L., Hewett, R., Stahler, S., & Mathieu, R. D. 1986, ApJ, 309, 275
Herbst, W., et al. 1986, ApJ, 310, L71
Herczeg, G. J., Linsky, J. L., Valenti, J. A., Johns-Krull, C. M., & Wood, B. E. 2002, ApJ, 572, 310
Herczeg, G. J., Wood, B. E., Linsky, J. L., Valenti, J. A., & Johns-Krull, C. M. 2004, ApJ, 607, 369
Hu, Y.-Q., Esser, R., & Habal, S. R. 2000, J. Geophys. Res., 105, 5093
Hummer, D. G., & Rybicki, G. B. 1968, ApJ, 153, L107
Johns-Krull, C. M., Valenti, J. A., & Linsky, J. L. 2000, ApJ, 539, 815
Kastner, J. H., Huenemoerder, D. P., Schulz, N. S., Canizares, C. R., & Weintraub, D. A. 2002, ApJ, 567, 434
Königl, A., & Pudritz, R. E. 2000, in Protostars and Planets IV, ed V. Mannings, A. P. Boss, & S. S. Russell (Tucson: Univ. Arizona Press), 799
Krist, J. E., Stapelfeldt, K. R., Menard, F., Padgett, D. L., & Burrows, C. J. 2000, ApJ, 538, 795
Lobel, A., & Dupree, A. K. 2001, ApJ, 558, 815
McLean, I. S., et al. 1998, Proc. SPIE, 3354, 566
Moos, H. W., et al. 2000, ApJ, 538, L1
Muzerolle, J., Calvet, N., Briceño, C., Hartmann, L., & Hillenbrand, L. 2000, ApJ, 535, L47
Pyo, T.-S., et al. 2003, ApJ, 590, 340
Raymond, J. C., Blair, W. P., & Long, K. S. 1997, ApJ, 489, 314
Redfield, S., Linsky, J. L., Ake, T. B., Ayres, T. R., Dupree, A. K., Robinson, R. D., Wood, B. E., & Young, P. R. 2002, ApJ, 581, 626
Shang, H., Glassgold, A. E., Shu, F. H., & Lizano, S. 2002, ApJ, 564, 853
Shu, F., Najita, J., Ostriker, E., Wilkin, F., Ruden, S., & Lizano, S. 1994, ApJ, 429, 781
Stassun, K. G., Ardila, D. R., Barsony, M., Basri, G., & Mathieu, R. D. 2004, AJ, 127, 3537
Takami, M., Chrysostomou, A., Bailey, J., Gledhill, T. M., Tamura, M., & Terada, H. 2002, ApJ, 568, L53
Walter, F. M., et al. 2003, AJ, 126, 3076
Young, P. R., Del Zanna, G., Landi, E., Dere, K. P., Mason, H. E., & Landini, M. 2003, ApJS, 144, 135