STELLAR WIND VARIATIONS DURING THE X-RAY HIGH AND LOW STATES OF CYGNUS X-1\textsuperscript{1,2}

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ABSTRACT

We present results from Hubble Space Telescope ultraviolet spectroscopy of the massive X-ray and black hole binary system, HD 226868 = Cyg X-1. The spectra were obtained at both orbital conjunction phases in 2002 and 2003, when the system was in the X-ray high/soft state. The UV stellar wind lines suffer large reductions in absorption strength when the black hole is in the foreground due to the X-ray ionization of the wind ions. We constructed model UV wind line profiles assuming that X-ray ionization occurs everywhere in the wind except the zone where the supergiant blocks the X-ray flux. The good match between the observed and model profiles indicates that the wind ionization extends to near the hemisphere of the supergiant facing the X-ray source. We also present contemporaneous spectroscopy of the H\textsc{o} emission that forms in the high-density gas at the base of the supergiant’s wind and the He ii $\lambda$4686 emission that originates in the dense, focused wind gas between the stars. The H\textsc{o} emission strength is generally higher in the high/soft state than in the low/hard state, but the He ii $\lambda$4686 emission is relatively constant between X-ray states. The results suggest that mass transfer in Cyg X-1 is dominated by the focused wind flow that peaks along the axis joining the stars, and that the stellar wind contribution from the remainder of the hemisphere facing the X-ray source is shut down by X-ray photoionization effects (in both X-ray states).

Subject headings: binaries: spectroscopic — stars: early-type — stars: individual (HD 226868, Cygnus X-1) — stars: winds, outflows — X-rays: binaries

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1. INTRODUCTION

The massive X-ray binary Cygnus X-1 is a seminal target in the study of gas dynamics in the vicinity of a stellar mass black hole. Its X-ray luminosity and energetic jets (Gallo et al. 2005) are powered by gas accretion from the nearby companion star HD 226868 (O9.7 Iab; Walborn 1973) in a spectroscopic binary with a 5.6 day orbital period. There are several ways in which mass transfer from the supergiant to the black hole may occur in this system (Kaper 1998). The O supergiant, like other massive and luminous stars, has a strong radiatively driven wind that may be partially accreted through the gravitational force of the black hole. The supergiant is large and is probably close to filling its critical Roche surface (Gies & Bolton 1986a; Herrero et al. 1995), so a gas stream through the inner L1 point may also be present. The actual gas flow in the direction of the black hole is probably intermediate between a spherically symmetric wind and a Roche lobe overflow stream, and there is evidence that the flow is best described as a focused wind (Friend & Castor 1982; Gies & Bolton 1986b; Gies et al. 2003; Miller et al. 2005). The gas ions responsible for accelerating the wind may become ionized in the presence of a strong X-ray source, leading to a lower velocity, “stalled” wind (Blondin et al. 1990; Stevens 1991). In situations of very high X-ray flux, photoionization may extend so close to the supergiant’s photosphere that the wind never reaches the stellar escape velocity, and thus ceases to become an X-ray accretion source (Day & Stevens 1993; Blondin 1994). However, such a high X-ray flux may heat the outer gas layers to temperatures where the thermal velocities exceed the escape velocity, to create a thermal wind that may fuel black hole accretion.

Important clues about the mass transfer process come from the temporal variations of the observed X-ray flux. Cyg X-1 is generally observed in either a low flux/hard spectrum state, with an X-ray spectrum that is relatively flat, or a high flux/soft spectrum state with a steeper power-law spectrum (Shaposhnikov & Titarchuk 2006). The gamma-ray portion of the spectrum is also elevated during the high/soft state (McConnell et al. 2002). The high/soft state usually lasts for periods of days to months, and the fraction of time observed in the high/soft state has increased from 10% in 1996–2000 to 34% since early 2000 (Wilms et al. 2000).
2006). This increase may be related to an overall increase in the supergiant’s radius in the period from 1997 to 2003–2004 that is suggested by changes in the long-term optical light curve (Karitskaya et al. 2006a). The system sometimes experiences so-called failed-state transitions, when it starts to increase in flux, but then stops at an intermediate state and returns to the low/hard state. All these transitions probably reflect changes in the inner truncation radius of the accretion disk surrounding the black hole that are caused by a variable accretion rate (largest when the system is in the high/soft state; Done 2002; McClintock & Remillard 2006). Thus, the temporal variations in the X-ray state offer us a means to compare the black hole accretion processes with observational signatures related to mass transfer.

The Hα emission formed in the high-density gas at the base of the stellar wind is an important diagnostic of the mass-loss rate in massive stars (Puls et al. 1996; Markova et al. 2005). The Hα emission variations in HD 226868 over the last few years are documented in independent spectroscopic investigations by Gies et al. (2003) and Tarasov et al. (2003). Both of these studies concluded that the Hα emission appears strongest when the system is in the low/hard X-ray state, while a range of weak to moderate emission strengths are observed during the high/soft states. This is a surprising result, since taken at face value, strong emission is associated with a large wind mass-loss rate, and the simplest expectation that the X-ray accretion flux increases with mass-loss rate is, in fact, not observed. There are several possible explanations. (1) A denser wind may be more opaque to X-rays. However, this seems unlikely because the observed inverse relation between Hα emission strength and X-ray flux is observed at all orbital phases, not just when the supergiant and its wind are in the foreground. (2) The X-ray source may photoionize and heat the gas responsible for the Hα emission, so that a larger X-ray flux leads to a decrease in Hα strength. This clearly occurs at some level, but both Gies et al. (2003) and Tarasov et al. (2003) argue that portions of the wind shaded from the ionizing flux also display significant temporal variations. (3) Changes in the X-ray flux will lead to variations in the ionized volume of gas surrounding the black hole, and consequently, the total acceleration of the wind in the direction toward the black hole will vary with the distance traveled before the atoms responsible for line-driving are ionized. Thus, a stronger, denser wind might reach a faster speed before ionization, and since the Bondi-Hoyle accretion rate varies as \( r^{-4} \), the gas captured by the black hole (and the associated X-ray flux) declines. This last process can be tested through direct study of the degree of wind ionization observed in the ultraviolet P Cygni lines formed in the supersonic part of the wind outflow. When the system is observed with the ionization region in the foreground, the absorption cores of these P Cygni lines will be truncated at a blueshift corresponding to the highest projected speed before encountering the ionization zone, the so-called Hatchett-McCray effect (Hatchett & McCray 1977). The binary is so faint in the ultraviolet that high dispersion spectra were very difficult to obtain with the International Ultraviolet Explorer (IUE) satellite (Davis & Hartmann 1983), but a good series of observations were obtained with IUE at lower spectral resolution, which clearly indicate the weakening of the wind lines when the black hole is in front (Treves et al. 1980; van Loon et al. 2001). Most of these spectra were obtained in the low/hard X-ray state (§ 5), when according to the varying wind strength model the mass loss rate is higher and the wind is less ionized and faster.

We embarked on a new program of high-S/N, high-dispersion UV spectroscopy to test this hypothesis with the Hubble Space Telescope Imaging Spectrograph (STIS). We obtained observations at the two orbital conjunction phases in both 2002 and 2003. These sets of observations were both made during the rare high/soft X-ray state, and planned observations during the low/hard state were unfortunately scuttled by the STIS electronics failure in 2004. However, we can rebin the high-quality HST spectra made during the high/soft state to the lower resolution of the IUE archival spectra (mostly low/hard state) in order to test whether or not the wind ionization state does in fact differ significantly between states. We describe a program of supporting optical spectroscopy we have obtained to check the orbital phase (§ 2) and wind strength (§ 3) at the times of the HST observations. We compare the Hα measurements with the contemporaneous X-ray light curve recorded with the Rossi

### Table 1: Journal of Spectroscopy

| Run Number | Range (HJD − 2450,000) | Resolving Power | Observatory/Telescope/Spec., Grating/Detector |
|------------|------------------------|-----------------|--------------------------------------------|
| 1          | 2419.8−2827.7          | 6510−6710       | 8900 70 DDO/1.88 m/Cass., 1800 g mm−1/Thomson 1024 × 1024 |
| 2          | 2448.7−2453.9          | 6530−6710       | 7400 15 KPNO/0.9 m/Coudé, B (order 2)/T10 |
| 3          | 2825.8−2828.9          | 6320−8970       | 2720 6 KPNO/0.9 m/Coudé, RC400 (order 1)/F3KB |
| 4          | 2826.8−2827.9          | 6353−6756       | 6900 10 DAO/1.85 m/Cass., 21121R/SITE-2 |
| 5          | 2730.7−2904.5          | 6258−6770       | 10900 24 Ondršejov/2 m/Coude, 700 mm/SITe 2000 × 800 |
| 6          | 2450.3−2453.3          | 1150−1740       | 14500 4 HST/2.4 m/STIS, G140M/FUV-MAMA |
| 7          | 2825.7−2827.8          | 1150−1740       | 14500 4 HST/2.4 m/STIS, G140M/FUV-MAMA |
| 8          | 2448.7−2454.0          | 4624−4740       | 13000 14 KPNO/0.9 m/Coudé, B (order 1)/T10 |
| 9          | 2824.9−2826.8          | 3759−5086       | 2990 3 KPNO/0.9 m/Coudé, RC400 (order 2)/F3KB |
| 10         | 2912.8−2915.8          | 4182−4942       | 5700 5 KPNO/4 m/RC Spec., BL380 (order 2)/T2KB |

### Table 2: Radial Velocity and Hα Equivalent Width Measurements

| HJD (−2,450,000) | Orbital Phase | \( V_r \) (km s\(^{-1}\)) | \( \Delta V_r \) (km s\(^{-1}\)) | \( O − C \) (km s\(^{-1}\)) | \( W_r(\lambda \text{H}\alpha) \) (Å) | Run Number |
|------------------|---------------|-----------------|-----------------|-----------------|-----------------|------------|
| 2419.847......... | 0.115          | 45.4            | 3.1             | 2.2             | −0.38           | 1          |
| 2426.848......... | 0.365          | 55.6            | 4.5             | 6.1             | −0.54           | 1          |
| 2427.841......... | 0.543          | −22.9           | 3.2             | 1.6             | −0.75           | 1          |
| 2429.605......... | 0.858          | −65.3           | 3.1             | −3.3            | −0.02           | 1          |
| 2443.803......... | 0.393          | 42.4            | 3.2             | 2.1             | −0.10           | 1          |
| 2445.846......... | 0.758          | −88.6           | 3.1             | −10.6           | −0.07           | 1          |
| 2446.804......... | 0.929          | −42.0           | 3.1             | −5.4            | −0.10           | 1          |
| 2448.694......... | 0.267          | 68.4            | 1.3             | 1.0             | 0.01            | 2          |
| 2448.850......... | 0.294          | 67.5            | 3.1             | 2.5             | 0.10            | 1          |
| 2448.954......... | 0.313          | 66.5            | 1.1             | 4.3             | −0.22           | 2          |

Note.—Table 2 is published in its entirety in the electronic edition of the *Astrophysical Journal*. A portion is shown here for guidance regarding its form and content.
X-ray Timing Explorer All-Sky Monitor instrument (Levine et al. 1996) and confirm our earlier result showing how H\alpha tends to strengthen as the X-ray flux declines (§ 3). We then describe the observed variations in the main UV wind lines and present a simple “shadow wind” model for the profiles (§ 4). We compare the variations observed in the \textit{HST} and \textit{IUE} spectra in § 5, and then reassess the question of the mass transfer process in § 6. We will discuss the photospheric features in the UV spectra in a forthcoming paper (S. M. Caballero Nieves et al., in preparation).

2. OBSERVATIONS AND ORBITAL EPHEMERIS

The \textit{HST} STIS spectra were obtained with the first-order G140M grating in a series of subexposures at different grating tilts in order to record the UV spectrum over the full available range (1150 to 1740 Å). Two full sets were made near each orbital conjunction phase in runs in both 2002 and 2003. All the spectra were reduced using the IDL software developed at NASA Goddard Space Flight Center for the STIS Instrument Definition Team. The spectra were rebinned on a log \(k\), heliocentric wavelength scale to a spectral resolution of \(R = 10000\) and rectified to a pseudocontinuum based on the flux in relatively line-free regions.

The space observations were supported by contemporaneous, ground-based observations of the red spectrum in the vicinity of H\alpha. These 125 spectra were made with the University of Toronto David Dunlap Observatory 1.88 m telescope, NOAO Kitt Peak National Observatory 0.9 m coude feed telescope, the Herzberg Institute of Astrophysics Dominion Astrophysical Observatory 1.85 m telescope, and the Academy of Sciences of the Czech Republic Astronomical Institute Ondrejov Observatory 2 m telescope. We also obtained a smaller set of 22 blue spectra that record the variations in the He\textsc{i} \(\lambda 4686\) line that probably form in the focused part of the wind (Gies & Bolton 1986b; Ninkov et al. 1987; Karitskaya et al. 2006b). A summary of all these observing runs is given in Table 1, which lists run number, range of heliocentric Julian dates of observation, spectral range recorded, spectral resolving power (\(R = \lambda / \Delta \lambda\), where \(\Delta \lambda = \text{FWHM of the line spread function}\)), number of spectra obtained, and details about the telescope, spectrograph, and detector. The spectra were reduced and transformed to rectified flux on a uniform heliocentric wavelength scale (as described in Gies et al. 2003).

Most of the red spectra also record the He\textsc{i} \(\lambda 6678\) absorption line, and we decided to measure the stellar radial velocity from

![Fig. 1.—Two depictions of the H\alpha profiles as a function of heliocentric radial velocity and orbital phase, and grouped according to X-ray state at the time of observation. The X-ray high/soft group was selected from observations made between HJD 2,452,100–2,452,550 and between HJD 2,452,770–2,452,880; all other times were assigned to the X-ray low/hard group (see Fig. 2). The upper panel in each shows the profiles with their continua aligned to the orbital phase of observation, while the lower panel is a gray-scale version of the profiles, with the first and last 20% of the orbit repeated to improve the sense of phase continuity. The gray-scale intensities represent the rectified spectral flux between 0.92 (black) and 1.12 (white). The white line in the gray-scale image shows the orbital velocity curve of the supergiant.](image-url)
this line to check on the orbital ephemeris at the time of the \textit{HST} observations. The radial velocities were measured in the same way as outlined by Gies et al. (2003), by fitting a Gaussian to the observations. The radial velocities were measured in the same way as outlined by Gies et al. (2003), by fitting a Gaussian to the line to check on the orbital ephemeris at the time of the conjunction \( T_{\text{IC}} \) occurs 0.17 days later than the prediction from Brockopp et al. (1999), and we will adopt this revised epoch for the definition of orbital phase throughout the paper. We omitted the \textit{HST} measurements from the orbital solution because of concerns about possible systematic differences in the velocities derived from the UV lines and He i \( \lambda 6678 \), but the \((O - C)\) residuals for the \textit{HST} measurements given in Table 2 show that the UV measurements are in reasonable agreement with the velocity curve derived from He i \( \lambda 6678 \).

3. WIND AND X-RAY STATES DURING THE \textit{HST} OBSERVATIONS

The optical red spectra were obtained with the primary goal of monitoring the gas density at the base of the stellar wind of the supergiant. The H\(\alpha \) observations of HD 226868 are summarized in two panels in Figure 1 according to the X-ray state at the time of observation (see Fig. 2). The top portions show plots of the profiles arranged by orbital phase, while the lower gray-scale images show the spectral flux interpolated in radial velocity and orbital phase. The white line in the lower image shows the radial velocity curve of the supergiant (Table 3). These figures show that most of the emission/absorption complex appears to follow the orbit of the supergiant, as expected for an origin in the supergiant wind. We measured the H\(\alpha \) equivalent width in the same way as before (Gies et al. 2003) by making a numerical integration over a 40 Å range centered on H\(\alpha \), and these measurements are listed in column (6) of Table 2. We estimate that the typical measurement error is ±0.1 Å (depending mainly on the S/N of the individual spectrum).

We show the time evolution of the H\(\alpha \) equivalent width for a total of 240 measurements from Gies et al. (2003) and the new observations in the top panel of Figure 2. The lower panel of this figure shows the daily average soft X-ray flux over the same interval from the All-Sky Monitor on the \textit{Rossi X-ray Timing Explorer} (Levine et al. 1996). These flux measurements are the quick-look results provided by the \textit{RXTE}/ASM team. The two arrows in the top panel indicate the times of the two \textit{HST} observing runs, which took place when Cyg X-1 was in the high/soft state. The new measurements confirm the trends described by Gies et al. (2003) and Tarasov et al. (2003) that the H\(\alpha \) emission tends to be stronger when the soft X-ray flux declines and that there is a considerable range in emission strength when the soft X-ray flux is large (see Fig. 1).

Figures 3 and 4 show a detailed view of the time evolution of the H\(\alpha \) emission strength and X-ray flux for the week surrounding the first \textit{HST} run in 2002. The arrows in the top panel show the times of the \textit{HST} observations for each orbital conjunction phase. The symbols in the bottom panel indicate the count rates in the 1.5–3 keV (+) and 5–12 keV (×) bands.

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\begin{figure}[ht]
\centering
\includegraphics[width=0.8\textwidth]{fig2}
\caption{Long-term variations in the H\(\alpha \) emission strength (top) and daily average soft X-ray flux (bottom). The two arrows in the top panel indicate the times of the \textit{STIS} observations that occurred during the X-ray high/soft state. The recent, more densely sampled observations show clearly how the H\(\alpha \) emission increases as the soft X-ray flux declines.}
\end{figure}

\begin{figure}[ht]
\centering
\includegraphics[width=0.8\textwidth]{fig3}
\caption{Variations in H\(\alpha \) emission strength (top) and X-ray flux for each dwell observation (bottom) for the week surrounding the first \textit{HST} run in 2002. The arrows in the top panel show the times of the \textit{STIS} observations for each orbital conjunction phase. The symbols in the bottom panel indicate the count rates in the 1.5–3 keV (+) and 5–12 keV (×) bands.}
\end{figure}
The other important optical emission line in the spectrum of HD 226868 is the He \textsc{ii} 4686 feature. Gies & Bolton (1986b) and Ninkov et al. (1987) found that this emission probably forms between the supergiant and black hole in a higher density and slower region of the wind, the focused wind predicted by Friend & Castor (1982). We obtained a limited number of spectra of the He \textsc{ii} 4686 feature (runs 8 and 9 in Table 1) at the times of the two \textit{HST} observation sets, and these observations show profile variations with orbital phase that are quite similar to those seen previously (Gies & Bolton 1986b; Ninkov et al. 1987; Karitskaya et al. 2006b). We present in Table 5 the observed equivalent width of the He \textsc{ii} 4686 emission/absorption complex (made by numerical integration between 4677 and 4695 Å) for spectra from these two runs and from a third run (run 10 in Table 1) that occurred when the system had returned to the X-ray low/hard state. There was no significant difference in the amount of He \textsc{ii} 4686 emission present between the times of the two X-ray states. We compare in Table 6 the averages of these measurements with earlier orbital phase averages (Gies & Bolton 1986a; Brocksopp et al. 1999) and time averages (Ninkov et al. 1987) of the emission strength that correspond mainly to times when the system had returned to the X-ray low/hard state. Note that Ninkov et al. (1987) report only the net emission equivalent width after subtraction of the photospheric absorption profile of the similar star HD 149038, and we estimate that this procedure increased the emission strength by 0.25 Å according to the plot of the spectrum of HD 149038 given in Figure 1 of Ninkov et al. (1987). We find that the He \textsc{ii} 4686 emission has remained more or less constant in strength over the decades of observation and between the X-ray states, and this suggests that the tidal gas stream toward the black hole experiences much less variation than does the global wind as observed in the H\textalpha\ emission line.

4. ORBITAL VARIATIONS IN THE UV WIND LINES

Our primary interest here is how the X-ray flux ionizes portions of the supergiant’s wind and how our line of sight through the ionized zones changes with orbital phase. We show in Figures 5, 6, and 7 the changes observed between conjunctions in the major UV wind lines of N \textsc{iv} \lambda\lambda 1238, 1242, Si \textsc{iv} \lambda 1393, 1402, and C \textsc{iv} \lambda 1548, 1550. In a companion paper, Vrtilek et al. (2008) show the variations observed in several other weaker lines. The top panel in each of these figures shows the variations in 2002 between the phases with the black hole behind (\(\phi = 0.0;\) solid line) and in the foreground of the supergiant (\(\phi = 0.5;\) dotted line), and the bottom panel shows the same for the 2003 run. The spectra are plotted as a function of radial velocity for the shorter wavelength component in the frame of the supergiant (according to the orbital solution in Table 3). All three of these transitions display a large reduction in the extent and depth of the blueshifted absorption component when the black hole is in the foreground (the Hatchett-McCrady effect). These changes reflect the X-ray photoionization and resulting superionization of these ions in the wind gas seen projected

\begin{table}
\centering
\caption{H\textalpha\ Equivalent Widths and X-Ray Flux Counts for the \textit{HST} Observation Times}
\begin{tabular}{llll}
HJD & Orbital & \(W_{\text{\alpha}}\) & Flux (1.5–3 keV) \\
(\(–2,450,000\)) & Phase & (Å) & (ASM counts) \\
2450.3 & 0.55 & -0.45 (15) & 52 (10) \\
2453.2 & 0.08 & -0.02 (10) & 60 (10) \\
2453.7 & 0.60 & -0.39 (10) & 50 (10) \\
2453.8 & 0.95 & -0.44 (10) & 42 (10) \\
\end{tabular}
\end{table}

\begin{table}
\centering
\caption{He \textsc{ii} \lambda 4686 Equivalent Width Averages}
\begin{tabular}{lllllll}
Observation Dates & \(W_s\) & \(\sigma(W_s)\) & Source \\
& (Å) & (Å) & \\
1971–1981 & -0.36 & 0.12 & Gies & Bolton (1986a) \\
1980–1984 & -0.29 & 0.09 & Ninkov et al. (1987) \\
1996–1998 & -0.25 & 0.12 & Brocksopp et al. (1999) \\
2002–2003 & -0.39 & 0.12 & This paper, high/soft state \\
2003 & -0.39 & 0.11 & This paper, low/hard state \\
\end{tabular}
\end{table}
against the supergiant. We also find some evidence of the associated reduction in the strength of the red emission component due to the loss of these gas ions in the outflow away from our line of sight when the black hole is in the background. The variations between conjunctions appear to be almost identical for the observations in 2002 and 2003, which is probably due to the very similar X-ray fluxes that existed at those times of observation (§3, Table 4).

The shapes of the wind profiles near orbital phase \( \phi = 0.5 \) suggest that the P Cygni absorption troughs have almost entirely disappeared, or that the wind ionization extends all the way toward the exposed photosphere of the supergiant. We made some simple calculations of the appearance of wind profiles that arise only from the gas hidden from the X-ray source, the so-called shadow wind (Blondin 1994) that is illustrated diagrammatically in Figure 8. Here we assume that the normal supergiant wind is confined to the region where the line of sight to the black hole is blocked by the supergiant. However, we expect that in reality this shadow region is partially exposed to X-rays by wind scattering (probably comparable to the scattering along our line of sight through the wind, i.e., a few percent of the unobscured X-ray flux; Wen et al. 1999) and by the Coriolis deflection that will bring the shadowed gas into regions of X-ray illumination (Blondin 1994). The line synthesis calculations are based on a modification of the Sobolev-Exact Integration method (Lamers et al. 1987) that was developed by van Loon et al. (2001). The simplifying assumption in this model is that the observer lies along the axis joining the stars at the two conjunctions (or that the orbital inclination is \( i = 90^\circ \)) and the orbital phases are \( \phi = 0.0 \) and 0.5). However, since the actual inclination is smaller (\( i = 33^\circ - 40^\circ \); Gies & Bolton 1986a; Brocksopp et al. 2002), our line

Fig. 5.— Spectral variations observed between conjunctions for the N v \( \lambda \lambda 1238, 1242 \) wind feature in both the 2002 (top) and 2003 (bottom) runs. The spectra are plotted as a function of Doppler shift for the blue component of the doublet in the rest frame of the supergiant (which leads to small offsets in the positions of the narrow, interstellar lines that are stationary in the absolute frame). Vertical line segments indicate the rest wavelength positions of both components of the doublet.

Fig. 6.— Spectral variations observed between conjunctions for the Si iv \( \lambda \lambda 1393, 1402 \) wind feature, in the same format as Fig. 5.

Fig. 7.— Spectral variations observed between conjunctions for the C iv \( \lambda \lambda 1548, 1550 \) wind feature, in the same format as Fig. 5.

Fig. 8.— Cartoon view of the binary from within the orbital plane. The normal wind ions are assumed to exist only within the shadow wind zone to the left of the supergiant (bounded by a thick dashed line), where the X-ray flux from the vicinity of the black hole (marked by “X”) is fully blocked, while the gas is ionized to higher levels in the rest of the wind. The simple model predictions are based on viewing the system along the line of centers (shown by arrows), while in fact we observe the supergiant at a lower inclination angle (\( i = 40^\circ \)) assumed). The dotted lines show the part of the line of sight that is projected onto the disk of the star at the two orbital phases for an observer at the correct direction with respect to the orbital plane. The shadow wind region projected against the star in each case is the area bounded by the surface of the star and the dashed and dotted line for that phase. CM marks the center of mass position.
Average observed spectra (solid line) and shadow wind model spectrum (connected diamonds) for the N v $\lambda 1238$, 1242 wind feature (plotted as a function of Doppler shift for the blue component of the doublet in the rest frame of the supergiant). The top panel shows the profiles for case where the black hole is in the background, while the bottom profile illustrates the other conjunction case, where the black hole is in the foreground (photoinizing the wind gas seen projected against the supergiant). The dotted line shows the predicted photospheric line spectrum (offset for clarity) from the models of Lanz & Hubeny (2003). Note that the latter representation does not include the broad Ly$\alpha$ wings that depress the continuum in the observed spectrum toward the left-hand side of the diagram.

The line synthesis is based on a set of adopted parameters and two fitting parameters. Most of the adopted parameters come from the study of Cyg X-1 and similar X-ray binaries by van Loon et al. (2001); in particular, we assume a wind velocity law exponent of $\gamma = 1$ (eq. [2] in van Loon et al. 2001), a semimajor axis equivalent to $2.1R_*$ (where $R_*$ is the radius of the supergiant; Gies & Bolton 1986a), and a characteristic turbulent velocity in the wind equal to $0.1v_\infty$ (Groenewegen et al. 1989), where $v_\infty$ is the terminal velocity in the undisturbed wind. The photospheric components corresponding to the wind transitions were assumed to be Gaussian in shape, with parameters set by Gaussian fits of the photospheric profiles in the non-LTE, line-blanketed model spectra of Lanz & Hubeny (2003) (for $T_{\text{eff}} = 30,000$ K, $\log g = 3.0$, $V \sin i = 100$ km s$^{-1}$, a linear limb darkening coefficient of $\epsilon = 0.50$, and a spectral resolving power of 10,000).

The final two parameters, the wind terminal velocity $v_\infty$ and the integrated optical depth through the shadow wind of the blue component of the transition $\tau$, were fit by trial and error in order to match the entire set of the three wind lines at each conjunction. Note that the value of $v_\infty$ is set mainly by fits of the profiles at orbital phase $\phi = 0.0$, when the undisturbed wind is in the foreground and projected against the star. The best match was made with $v_\infty = 1200$ km s$^{-1}$ and $\tau = 6, 4$, and 10 for the N v, Si iv, and C iv features, respectively. The shadow wind model profiles are presented in Figures 9, 10, and 11 for these three wind lines. The top panel in these figures shows the model (diamonds) and average observed spectra (solid line) for $\phi = 0.0$, while the lower panel illustrates the same for phase $\phi = 0.5$ (black hole in the foreground). The model profiles were renormalized in flux in each case to match the pseudocontinuum beyond the line wings in the observed spectra. Each panel also contains the predicted photospheric spectrum for the region from the models of Lanz & Hubeny (2003). These representative fits successfully reproduce many of the profile characteristics, especially when line blending from the other photospheric lines is taken into account. This suggests that the geometry of the photoionization zone is probably not too different from that assumed for a shadow wind (at least for the high/soft X-ray state). However, we caution again that our fitting parameters are based on an axial viewing orientation, while our actual view is more oblique. For example, according to the geometry sketched in Figure 8 (for $i = 40^\circ$), the fastest moving part of the shadow wind that is projected against the supergiant at $\phi = 0.0$ occurs at a radial distance from the center of the supergiant of $\approx 4.6R_*$, where the wind has not yet reached terminal velocity. Thus, our fit value of $v_\infty = 1200$ km s$^{-1}$ is probably well below the actual value (which is probably closer to 1600 km s$^{-1}$).
The low orbital inclination and the subsequent limited projection of the shadow wind region against the disk of the photosphere results in P Cygni absorption troughs that are unusually weak for the spectra of supergiants like HD 226868. We show in Figures 12 and 13 montages of the Si iv and C iv wind features in four other O9.7 lab supergiants as seen in high-dispersion spectra from the IUE archive. The mean spectrum of HD 226868 at orbital phase $\phi = 0.0$ (shown at the top of both figures) shows that the wind profiles have a lower optical depth and attain a smaller blueshifted velocity because only a small portion of the shadow wind is projected against the disk of the supergiant at its inferior conjunction (see Fig. 8).

5. COMPARISON OF THE WIND LINES IN THE X-RAY LOW AND HIGH STATES

Our original goal was to obtain another set of STIS spectra when Cyg X-1 was in the low/hard X-ray state in order to determine how the wind ionization conditions change with X-ray state. With the loss of STIS, such a comparison is not possible at present. However, the low-dispersion FUV spectra of HD 226868 made with IUE were in most cases made when Cyg X-1 was in the low/hard state. Thus, we can investigate differences in the wind ionization properties between X-ray states through a comparison of the HST high/soft state spectra with the IUE low/hard state spectra.

We collected 30 low-dispersion, short-wavelength prime camera spectra of HD 226868 from the IUE archive, and transformed these to rectified flux versions on a uniform wavelength grid. Next, we smoothed, rectified, and rebinned the HST STIS spectra onto the same IUE wavelength grid, so that the line blended structures would appear the same as they do in the IUE spectra. We then measured the effective absorption strength by determining the mean flux across a spectral range that extends over the full range of the apparent wind feature (as done by van Loon et al. 2001). This average flux will reflect both the changing P Cygni absorption and the other line blends (including interstellar components), but since the latter are generally constant in time, the average flux will serve to show the relative variations in the wind absorption (low flux when the P Cygni trough is deep and high flux when the trough weakens).

The average flux measurements for both the IUE and rebinned HST spectra are given in Table 7, which lists the heliocentric Julian date of midexposure, orbital phase (from Table 3), the mean rectified flux across the Si iv and C iv wind lines, the telescope of origin, the X-ray state at the time of the observations, and a code for references discussing the contemporary X-ray fluxes. Note that we did not measure the N v transition in the IUE spectra because these spectra are poorly exposed at the short-wavelength end. The IUE average flux measurements have a typical error of $\pm 7\%$, based on the scatter in the results from closely separated pairs of spectra.

The average fluxes across the wind lines are plotted as a function of orbital phase in Figures 14 and 15 for Si iv and C iv, respectively (see a similar depiction in Fig. 1 from van Loon et al. 2001). Different symbols show these measurements for the different X-ray states as observed with IUE and HST. We suspect that despite our efforts to rectify the IUE and HST spectra in the same way, there are probably still some systematic differences, since the mean fluxes for the HST spectra appear to be somewhat lower than those for the IUE spectra. Nevertheless, the amplitude of line strength variation appears to be more or less the same in each of the IUE low/hard state, IUE high/soft state, and HST high/soft state spectra. This result indicates that the Hatchett-McCray effect (and the amount of wind photoionization it represents) occurs at about the same level in both X-ray states.

6. DISCUSSION

The X-ray accretion flux of Cyg X-1 is fueled by mass transfer from the supergiant. We argue in this section that the mass transfer process is dominated by a wind focused along the axis joining the stars. However, the accretion of this gas by the black hole may be influenced by the strength of the radiatively driven shadow wind, which is directed away from the black hole. We begin by reviewing the most pertinent observational results from this investigation, and then we consider the interplay between the dynamics of the wind outflow and the X-ray accretion flux.

First, the HST STIS spectra of HD 226868 that we obtained at two epochs when the system was in the high/soft state show dramatic variations in the wind line strength, which result from a superionization of the gas atoms illuminated by the X-ray flux. Shadow wind models, in which the wind ions only exist in the...
region where X-rays are blocked by the supergiant, make a reasonably good match to the observed profile variations, so we suspect that X-ray photoionization dominates much of the zone between the black hole and the facing hemisphere of the supergiant. A similar degree of wind ionization probably also exists in the X-ray low/hard state, since similar orbital variations in wind line strength are found in IUE low-dispersion spectra made during the X-ray low/hard state.

Second, the HST spectra suggest that stellar wind gas emanating from parts of the photosphere facing the X-ray source attains only a small velocity before becoming photoionized. For example, the highest optical depth wind feature, C\(\text{iv}\) \(\lambda\lambda 1548, 1550\), shows only a very modest P Cygni absorption core at phase \(\phi = 0.5\) (see Fig. 11), which extends blueward no more than about \(-400\) km s\(^{-1}\) (and it is possible that this small component results from a minor part of shadow wind projected against supergiant at \(\phi = 0.5\); see Fig. 8). This very low wind speed is probably less than the stellar escape velocity (~700 km s\(^{-1}\) near the poles).

These results from the UV wind lines indicate that very little mass loss is occurring by a radiatively driven wind for surface regions that are exposed to the X-ray source. The fact that the wind features appear similarly weak in IUE spectra obtained in the low/hard state suggests that a spherical, radiatively driven wind from the hemisphere of the supergiant facing the black hole is probably always weak or absent, and thus, accretion from a spherically symmetric wind must play a minor role in feeding the black hole in Cyg X-1.

On the other hand, we found that the emission equivalent width of the He\(\text{ii}\) \(\lambda 4686\) line is consistently strong between X-ray states and over the available record of observation. The orbital phase variations of this spectral feature (Gies & Bolton 1986b; Ninkov et al. 1987) are successfully matched by models of emission from an enhanced density and slower gas outflow region between the stars that is expected for a focused stellar wind (Friend & Castor 1982). Thus, while X-ray ionization reduces the wind outflow away from the axis joining the stars, the X-ray flux is apparently insufficient to stop the outflow in

| Orbital Phase | Mean Flux (Si iv \(\lambda\lambda 1400\)) | Mean Flux (C iv \(\lambda\lambda 1550\)) | X-Ray State | Reference |
|--------------|---------------------------------|---------------------------------|-------------|-----------|
| low 1, 2, 3  | 1.079                           | 0.622                           | IUE         | low 1, 2, 3|
| low 1, 2, 3  | 1.109                           | 0.725                           | IUE         | low 1, 2, 3|
| low 1, 2, 3  | 1.094                           | 0.691                           | IUE         | low 1, 2, 3|
| low 1, 2, 3  | 0.854                           | 0.632                           | IUE         | low 1, 2, 3|
| low 1, 2, 3  | 1.099                           | 0.756                           | IUE         | low 1, 2, 3|
| low 1, 2, 3  | 0.898                           | 0.667                           | IUE         | low 1, 2, 3|
| low 1, 2, 3  | 1.069                           | 0.765                           | IUE         | low 1, 2, 3|
| low 1, 2, 3  | 0.963                           | 0.733                           | IUE         | low 1, 2, 3|
| low 1, 2, 3  | 0.901                           | 0.649                           | IUE         | low 1, 2, 3|
| low 1, 2, 3  | 0.995                           | 0.789                           | IUE         | low 1, 2, 3|
| low 1, 2, 3  | 0.753                           | 0.588                           | IUE         | low 1, 2, 3|
| low 1, 2, 3  | 0.932                           | 0.678                           | IUE         | low 1, 2, 3|
| low 1, 2, 3  | 0.886                           | 0.671                           | IUE         | low 1, 2, 3|
| low 1, 2, 3  | 0.795                           | 0.648                           | IUE         | low 1, 2, 3|
| low 1, 2, 3  | 0.814                           | 0.610                           | IUE         | low 1, 2, 3|
| low 1, 2, 3  | 0.843                           | 0.654                           | IUE         | low 1, 2, 3|
| low 1, 2, 3  | 0.843                           | 0.533                           | IUE         | low 1, 2, 3|
| low 1, 2, 3  | 0.887                           | 0.696                           | IUE         | low 1, 2, 3|
| low 1, 2, 3  | 0.739                           | 0.548                           | IUE         | low 1, 2, 3|
| low 1, 2, 3  | 0.929                           | 0.683                           | IUE         | high 5    |
| low 1, 2, 3  | 0.817                           | 0.577                           | IUE         | high 5    |
| low 1, 2, 3  | 0.924                           | 0.764                           | IUE         | high 5    |
| low 1, 2, 3  | 1.009                           | 0.805                           | IUE         | high 5    |
| low 1, 2, 3  | 0.840                           | 0.678                           | IUE         | high 5, 6 |
| low 1, 2, 3  | 0.790                           | 0.584                           | IUE         | high 5, 6 |
| low 1, 2, 3  | 0.993                           | 0.746                           | IUE         | high 5, 6 |
| low 1, 2, 3  | 0.962                           | 0.757                           | IUE         | high 5, 6 |
| low 1, 2, 3  | 0.947                           | 0.714                           | HST         | high 7    |
| low 1, 2, 3  | 0.947                           | 0.722                           | HST         | high 7    |
| low 1, 2, 3  | 0.752                           | 0.515                           | HST         | high 7    |
| low 1, 2, 3  | 0.761                           | 0.520                           | HST         | high 7    |
| low 1, 2, 3  | 1.030                           | 0.743                           | HST         | high 7    |
| low 1, 2, 3  | 1.014                           | 0.725                           | HST         | high 7    |
| low 1, 2, 3  | 0.804                           | 0.551                           | HST         | high 7    |
| low 1, 2, 3  | 0.787                           | 0.530                           | HST         | high 7    |

References.—(1) Ling et al. 1983; (2) Kemp et al. 1981; (3) Priedhorsky et al. 1983; (4) Perotti et al. 1986; (5) Ogawara et al. 1982; (6) Oda 1980; (7) This paper.
the denser gas of the focused wind (the result of both tidal and radiative forces). Consequently, it is this focused wind component that is probably the primary means of mass transfer in Cyg X-1. We caution that the relative constancy of the He ii \( \lambda 4686 \) emission flux does not necessarily imply that the mass-loss rate in the focused wind is also steady. For example, the increased X-ray photoionization during the high/soft state may lead to an increase in He ii \( \lambda 4686 \) emission (see Fig. 2 in Gies & Bolton 1986b), so that a lower mass loss rate but higher ionization fraction might result in the same amount of observed emission. However, the presence of the He ii \( \lambda 4686 \) emission in both X-ray states indicates that focused wind mass loss always occurs at some level.

Finally, we confirm that the H\( \alpha \) P Cygni line forms mainly in the base of the stellar wind of the supergiant, since we observe that H\( \alpha \) follows the orbital velocity curve of the supergiant (Fig. 1). The new observations are consistent with earlier results (Gies et al. 2003; Tarasov et al. 2003) in demonstrating that the H\( \alpha \) emission strength is generally weaker in the high/soft X-ray state. Moreover, the low-resolution \textit{IUE} spectra indicate that outflow velocities in the direction of the black hole (as measured in blue side of the black hole, and while gas passing closer to the black hole is in the foreground. The \textit{IUE} flux measurements have a typical error of \( \pm 7\% \).

If this scenario is correct, then we expect that the outflow velocities in the direction of the black hole (as measured in blue extent of the P Cygni lines at phase \( \phi = 0.5 \)) will be larger than the supergiant escape velocity during the X-ray low/hard state. The superb quality \textit{HST}/STIS spectra indicate that outflow velocities are too low to launch the wind during the X-ray high/soft state. Moreover, the low-resolution \textit{IUE} spectra from the low/hard state appear to show a very similar pattern of the loss of the P Cygni absorption at \( \phi = 0.5 \) (Fig. 12 and 13), indicating that significant ionization zones still exist in the low/hard state. Taken at face value, these \textit{IUE} results suggest that the spherical component of wind outflow toward the black hole is weak and slow in both X-ray states, so a wind speed modulation is probably not the explanation for the accretion variations associated with the X-ray states. We will require new, high-quality UV spectroscopy of Cyg X-1 during the low/hard state in order to make a definitive test of this idea.

The radiatively driven wind of the supergiant leads to effective mass loss only in the X-ray shadowed hemisphere and in the focused wind between the stars in Cyg X-1. The outflow in the shadow wind region will experience a Coriolis deflection, so that the trailing regions of the shadow wind will eventually enter the zone of X-ray illumination (Blondin 1994). Once photoionized, this gas will stall with the loss of the important ions for radiative acceleration, and some of this slower gas may extend around the orbital plane to the vicinity of the black hole. Although this deflected wind gas is probably not a major accretion source (Blondin 1994), it may affect the accretion dynamics of the focused wind. For example, when the shadow wind mass loss rate is high (times of strong H\( \alpha \) emission), the resulting stalled wind component will create a higher ambient gas density on the leading side of the zone surrounding the black hole. The focused wind flow will make a trajectory toward the following side of the black hole, and while gas passing closer to the black hole will merge into an accretion disk, gas farther out will tend to
move past the black hole before turning into the outskirts of the disk. The presence of the stalled gas on the leading side may deflect past this outer, lower density part of the flow and effectively inhibit gas accretion from the focused wind. The subsequent reduction in gas accretion by the black hole may correspond to the conditions required to produce the low/hard X-ray state, while conversely, a reduction in the stalled gas from the shadow wind may promote mass accretion and produce the high/soft state (Brocksopp et al. 1999; Done 2002; McClintock & Remillard 2006). Clearly, new hydrodynamical simulations are needed to test whether the stalled wind component is sufficient to alter the accretion of gas from the focused wind and create the environments needed for the X-ray transitions.

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