WIND ACCRETION AND STATE TRANSITIONS IN CYGNUS X-1

D. R. Gies,2,3,4 C. T. Bolton,2 J. R. Thomson,5 W. Huang,2,3 M. V. McSwain,2,3,4 R. L. Riddle,2,3,4,6 Z. Wang,2,3,7 P. J. Witte,2 D. W. Wingert,2,3 B. Csák,8,9 and L. L. Kiss8,9

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ABSTRACT

We present the results of a spectroscopic monitoring program (from 1998 to 2002) of the Hα emission strength in HDE 226868, the optical counterpart of the black hole binary Cyg X-1. The feature provides an important probe of the mass-loss rate in the base of the stellar wind of the supergiant star. We derive an updated ephemeris for the orbit based on radial velocities measured from He i 6678. We list net equivalent widths for the entire Hα emission/absorption complex, and we find that there are large variations in emission strength over both long (years) and short (hours to days) time spans. There are coherent orbital phase–related variations in the profiles when the spectra are grouped by Hα equivalent width. The profiles consist of (1) a P Cygni component associated with the wind of the supergiant, (2) emission components that attain high velocity at the conjunctions and that probably form in enhanced outflows both toward and away from the black hole, and (3) an emission component that moves in antiphase with the supergiant’s motion. We argue that the third component forms in accreted gas near the black hole and that the radial velocity curve of the emission is consistent with a mass ratio of $M_X/M_{\text{opt}} \approx 0.36 \pm 0.05$. We find that there is a general anticorrelation between the Hα emission strength and X-ray flux (from the Rossi X-Ray Timing Explorer All Sky Monitor) in the sense that when the Hα emission is strong ($W_\lambda < -0.5$ Å) the X-ray flux is weaker and the spectrum harder. On the other hand, there is no correlation between Hα emission strength and X-ray flux when Hα is weak. We argue that this relationship is not caused by wind X-ray absorption nor by the reduction in Hα emissivity by X-ray heating. Instead, we suggest that the Hα variations track changes in wind density and strength near the photosphere. The density of the wind determines the size of X-ray ionization zones surrounding the black hole, and these in turn control the acceleration of the wind in the direction of the black hole. During the low/hard X-ray state, the strong wind is fast and the accretion rate is relatively low, while during the high/soft state, the weaker, highly ionized wind attains only a moderate velocity and the accretion rate increases. We argue that the X-ray transitions from the normal low/hard to the rare high/soft state are triggered by episodes of decreased mass-loss rate in the supergiant donor star.

Subject headings: binaries: spectroscopic — stars: early-type — stars: winds, outflows — X-rays: binaries

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1. INTRODUCTION

Cygnus X-1 has been one of the most intensively studied X-ray sources in the sky since its discovery and identifica-

1 Based on data obtained at the David Dunlap Observatory, University of Toronto.
2 Center for High Angular Resolution Astronomy, Department of Physics and Astronomy, Georgia State University, Atlanta, GA 30303; gies@chara.gsu.edu, huang@chara.gsu.edu, mcswain@chara.gsu.edu, witte@chara.gsu.edu, wingert@chara.gsu.edu.
3 Visiting Astronomer: Kitt Peak National Observatory, National Optical Astronomy Observatory, under contract with the National Science Foundation.
4 Visiting Astronomer: McDonald Observatory, University of Texas at Austin.
5 David Dunlap Observatory, University of Toronto, P.O. Box 360, Richmond Hill, ON L4C 4Y6, Canada; bolton@astro.utoronto.ca, jthomson@crux.astro.utoronto.ca.
6 Current address: Department of Physics and Astronomy, Iowa State University, Ames, IA 50011; riddle@iastate.edu.
7 Current address: Center for Space Research, Massachusetts Institute of Technology, 70 Vassar Street, Building 37, Cambridge, MA 02139; wangzx@space.mit.edu.
8 Department of Experimental Physics and Astronomical Observatory, University of Szeged, Dóm tér 9., Szeged, H-6720, Hungary; csakk@physx.u-szeged.hu, l.kiss@physx.u-szeged.hu.
9 Visiting Astronomer, University of Toronto David Dunlap Observatory.

tion with the O9.7 Iab supergiant star, HDE 226868 (Bolton 1972; Webster & Murdin 1972). This system provided the first evidence for the existence of stellar mass black holes when it was discovered to be a 5.6 day binary with a massive, unseen companion. Gies & Bolton (1986a) used the spectroscopic orbit (Gies & Bolton 1982; LaSalata et al. 1998; Brockopp et al. 1999b), light curve (Kemp et al. 1983; Karitskaya et al. 2001), photospheric line broadening, and a range in the assumed degree of Roche filling of the supergiant to obtain mass estimates of $M_{\text{opt}} = 23-43 M_\odot$ and $M_X = 10-21 M_\odot$. Herrero et al. (1995) derived physical parameters for the visible supergiant based on a spectroscopic analysis of the line spectrum, and they adopted a system inclination of $i = 35^\circ$ (based on published estimates) to arrive at mass estimates of 18 and 10 $M_\odot$ for the supergiant and black hole, respectively (the derived masses scale as $\sin^2 i$ over the probable range of $i = 30^\circ-40^\circ$; Gies & Bolton 1986a; Wen et al. 1999). The X-ray source in Cyg X-1 is powered mainly by accretion from the strong stellar wind of the supergiant star (Pettersson 1978; Kaper 1998). In fact, Cyg X-1 probably represents a situation intermediate between pure, spherical wind accretion and accretion by Roche lobe overflow. Observations of the optical emission lines (Gies & Bolton 1986b; Ninkov, Walker, & Yang 1987) indicate that the wind departs from spherical symmetry and that there exists an enhanced wind flow (or “focused
wind”) in the direction of the companion. The intense X-ray emission is believed to be produced close to the black hole in an accretion disk that emits soft X-ray photons and in a hot corona that inverse Compton scatters low-energy photons to higher energies (Liang & Nolan 1984; Tanaka & Lewin 1995). Ultraviolet radiation from close to the black hole has been detected through High Speed Photometer observations with the Hubble Space Telescope (Dolan 2001). Radio jets were recently discovered in Cyg X-1 (Stirling et al. 2001; Fender 2001), indicating a collimated outflow with a speed in excess of 0.6c, so that Cyg X-1 joins the group of Galactic microquasars, small-scale versions of active galactic nuclei (Mirabel & Rodríguez 1999). The target is also a candidate γ-ray transient source (Golenetskii et al. 2002); the γ-rays are probably created through inverse Compton scattering in the jets.

Cyg X-1 is generally found in either a low/hard state (the more common case of low 2–10 keV flux and a hard energy spectrum) or a high/soft state (in which the soft X-ray flux increases dramatically and the spectrum softens; Zhang et al. 1997; Zdziarski et al. 2002). Every few years Cyg X-1 makes a transition from the low/hard to the high/soft state, and it remains in this active state for weeks to months before returning to the low/hard state. The last well-documented high/soft state occurred in 1996 (Brocksopp et al. 1999a), and in 2001 September Cyg X-1 once again entered a high/soft state, which lasted until 2002 October. This recent transition into the high/soft state was accompanied by a sudden decrease in radio flux (Pooley 2001; the opposite of the radio emission line in HDE 226868 (A˚ Observatory/Telescope/Grating/CCD 0.71 KPNO/0.9 m/B/F3KB 3.5)), which we find to 2. OBSERVATIONS AND ORBIT

The 115 optical spectra were made from three different sites over the period from 1998 August to 2002 May, and we list in the final column of Table 1 the specific telescope and spectrograph combination associated with each observation. The majority of the spectra were obtained with the Kitt

| HJD    | Orbital Phase | $V_r$ (km s$^{-1}$) | $(O - C)$ (km s$^{-1}$) | $W_r$ (Å) | Observatory/Telescope/Grating/CCD |
|--------|---------------|---------------------|-------------------------|-----------|----------------------------------|
| 1053.7473 | 0.157        | 52.54               | -3.5                    | -0.73     | KPNO/0.9 m/B/F3KB                 |
| 1053.7687 | 0.160        | 58.1                | 1.1                     | -0.83     | KPNO/0.9 m/B/F3KB                 |
| 1055.7247 | 0.510        | -4.5                | 7.1                     | -0.91     | KPNO/0.9 m/B/F3KB                 |
| 1055.7830 | 0.520        | -9.1                | 7.4                     | -0.91     | KPNO/0.9 m/B/F3KB                 |
| 1056.7965 | 0.696        | -79.0               | -0.7                    | -1.57     | KPNO/0.9 m/B/F3KB                 |
| 1056.7908 | 0.700        | -81.3               | -2.4                    | -1.71     | KPNO/0.9 m/B/F3KB                 |
| 1057.7635 | 0.874        | -68.2               | -7.5                    | -1.53     | KPNO/0.9 m/B/F3KB                 |
| 1057.7864 | 0.878        | -66.0               | -6.6                    | -1.66     | KPNO/0.9 m/B/F3KB                 |
| 1058.7556 | 0.051        | 23.2                | 6.4                     | -0.71     | KPNO/0.9 m/B/F3KB                 |
| 1058.7766 | 0.055        | 25.6                | 7.1                     | -0.90     | KPNO/0.9 m/B/F3KB                 |

Note.—Table 1 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.
Peak National Observatory 0.9 m coudé feed telescope in conjunction with a program on SS 433. Details about these observations are given in Gies et al. (2002). During the observing runs in 1998 and 2000, we used the long collimator, grating B (in second order with order sorting filter OG550), camera 5, and a Ford 3072 × 1024 CCD (F3KB) detector. This arrangement produced a resolving power \( R = \lambda/\Delta \lambda = 9530 \) and covered a range of 829 Å around H\( \alpha \). The KPNO coudé feed runs in 1999, however, relied on the short collimator, grating RC181 (in first order with a GG495 filter to block higher orders), and camera 5 with the same F3KB detector, and this setup provided lower resolving power, \( R = 4630 \), but broader spectral coverage (1330 Å). We usually obtained two consecutive exposures of 30 minutes duration and co-added these spectra to improve the signal-to-noise ratio. We also observed the rapidly rotating A-type star, \( \zeta \) Aql, which we used for removal of atmospheric water vapor lines. Each set of observations was accompanied by numerous bias, flat-field, and Th Ar comparison lamp calibration frames.

We also obtained in 1999 several high-dispersion echelle spectra using the University of Texas McDonald Observatory 2.1 m telescope and Sandiford Cassegrain Echelle Spectrograph (McCarthy et al. 1993). The detector was a Reticon 1200 × 400 CCD (RA2) with 27 μm square pixels that recorded 27 echelle orders covering the region blueward from H\( \alpha \) with a resolving power of \( R = 42,000 \). The exposure times were typically 30 minutes. The observations from 2001 to 2002 were made with the University of Toronto David Dunlap Observatory (DDO) 1.9 m telescope. The DDO spectra were obtained with the Cassegrain spectrograph and a Thomson 1024 × 1024 CCD. All but one of these spectra were made with a 1800 grooves mm\(^{-1} \) grating that yielded a resolving power of \( R = 11,200 \). The exposure times were usually 20 minutes.

The spectra were extracted and calibrated using standard routines in IRAF.\(^{10} \) All the spectra were rectified to a unit continuum by the fitting of line-free regions using the IRAF task “continuum” (and in the case of the echelle spectra, the resulting orders were then linked together using the task “scombine”). The removal of atmospheric lines was done by creating a library of telluric standard spectra from each run, removing the broad stellar features from these, and then dividing each target spectrum by the modified atmospheric spectrum that most closely matched the target spectrum in a selected region dominated by atmospheric absorptions. The spectra from each run were then transformed to a common heliocentric wavelength grid. The higher resolution spectra were smoothed to the nominal, 2 pixel resolution of the lower resolution spectra obtained with the KPNO coudé feed and the RC181 grating. This degradation in resolution is inconsequential for the analysis of the broad structures in H\( \alpha \) that we describe here.

We discuss below the spectral variations related to orbital phase, and in order to determine an accurate ephemeris for the orbit, we decided to measure radial velocities using the photospheric line He\( \lambda 6678 \). The red wing of this feature is blended with He\( \pi \lambda 6683 \), which occasionally is filled in with weak, P Cygni–type emission (also observed in He\( \lambda 5876 \)). We measured radial velocities by fitting a Gaussian function to the central line core in order to avoid some of these problems with the line wings, but our final results are probably influenced by the varying strength of the P Cygni emission. We also measured the position of the interstellar line at 6613.56 Å in order to correct for small differences in the wavelength calibration from the different spectrographs (this line is clear of the nearby N\( \pi \lambda 6610 \) emission line of the supergiant). We measured these differences by cross-correlating the profile of the interstellar line in each spectrum with the same profile obtained at KPNO on HJD 2,451,425.8079, and the measured stellar radial velocities were adjusted according to these cross-correlation shifts. The final radial velocity measurements are listed in Table 1.

We made a solution of the orbital elements using the non-linear, least-squares fitting program of Morbey & Brosterhus (1974). All the radial velocities were assigned the same weight in computing the solution, and we assumed a circular orbit (Gies & Bolton 1982). A first trial solution with a fitted period resulted in an orbital period that was the same within errors as that derived by Brocksopp et al. (1999b) based on all the available radial velocity data, and since the data used by Brocksopp et al. (1999b) span a 26 yr interval, we decided to fix the period at their value, \( P = 5.599829 \pm 0.000016 \) days. We then solved for the remaining parameters: the epoch of supergiant inferior conjunction \( \mathcal{T}(IC) \), the semiamplitude \( K \), and systemic velocity \( V_0 \). The measurements and radial velocity curve are shown in Figure 1, and our solution is compared to that of Brocksopp et al. (1999b) in Table 2. This table also lists the rms residuals from the fit \( \sigma \), the mass function \( f(m) \), and the projected component of the semimajor axis \( a_1 \sin i \). The individual observed minus calculated residuals \( (O - C) \) and orbital phases \( \phi \) are given in Table 1. Our derived epoch is 0.043 ± 0.013 days later than that predicted by ephemeris of Brocksopp et al. (1999b), and we use our new result in what follows. The semiamplitude is in good agreement with prior work (Gies & Bolton 1982; LaSalva et al. 1998; Brocksopp et al. 1999b), but the systemic velocity is somewhat low because of the subtle P Cygni emission in He\( \lambda 6678 \) (which causes the absorption core to

\(^{10} \) IRAF is distributed by the National Optical Astronomy Observatory, which is operated by the Association of Universities for Research in Astronomy, Inc., under cooperative agreement with the National Science Foundation.
appear slightly blueshifted). Thus, our estimate of $V_0$ is probably smaller than the physical systemic velocity of the binary.

### 3. Hα VARIABILITY

The Hα feature is regarded as a reliable source for the determination of the mass-loss rate in luminous hot stars (Puls et al. 1996). The line appears as an absorption profile in stars with small mass-loss rates, and it grows into a strong emission profile in stars with well-developed winds. The emission forms by recombination, and since this process depends on the square of the gas density, the Hα emission serves as a probe of the dense, basal wind near the stellar photosphere. The observational evidence to date demonstrates that the Hα emission is also time variable, especially in luminous supergiants like the visible star in Cyg X-1. Kaper et al. (1998) show an example of large Hα emission variations over the course of a few days in the O9.5 Ib star, ζ Ori, which presumably result from changes in the wind density and structure. Kaper et al. (1997) discuss several cases of cyclical variability in Hα that are related to the rotational period of the star. The Hα feature in Cyg X-1 appears to be cyclically variable with the orbital period (Hutchings et al. 1974; Hutchings, Crampton, & Bolton 1979; Ninkov et al. 1987; Sowers et al. 1998), but these earlier investigations were too limited in time coverage to reveal the large variations that can occur that are unrelated to orbital phase. Both kinds of variability offer important clues about the structure and density of the wind outflow that is the ultimate source of the accretion-fed X-ray luminosity.

The Hα profiles in Cyg X-1 are often complex in appearance, and we decided to begin our analysis by measuring the overall emission strength through a simple numerical integration of the line intensity (including both emission and absorption portions). This equivalent width, $W_\lambda$, was measured over a 40 Å range centered on Hα, and our results are listed in the fifth column of Table 1. The measurement errors can be estimated from the values obtained during the final KPNO coude’ feed run, when Cyg X-1 was usually observed twice each night. Since the emission variations generally occur on longer timescales (days), the scatter within a night mainly reflects measurement errors. The mean of the differences in equivalent width within each night indicates typical measurement errors of ±0.08 Å.

We find that the equivalent width varied from 0.3 Å (absorption stronger than emission) to −1.7 Å (emission much stronger than absorption) over the course of our observations (see Fig. 10). The variations have both a long-term component (significant differences between the mean equivalent widths of the individual observing runs) and a rapid component (large night-to-night changes). The emission generally weakened between 1998 and 2002. A periodogram search indicated a possible small amplitude variation with a period of 156 ± 8 days, which is similar to the long X-ray and radio period of 142 ± 7 days found by Brocksopp et al. (1999a). However, our sampling is too fragmentary to characterize accurately variations on timescales of months, and we focus here on profile variations that are related to orbital phase. We found that these were best seen when the profiles were grouped into samples with similar Hα equivalent width. Figures 2, 3, and 4 illustrate the profiles as a function of heliocentric radial velocity and orbital phase for times between 1998 and 2000 of strong ($W_\lambda < −0.9$ Å), moderate ($−0.9$ Å $< W_\lambda < −0.4$ Å), and weak ($W_\lambda > −0.4$ Å) Hα emission, respectively. Figure 5 shows the same for the DDO spectra (2001–2002), obtained during the high/soft X-ray state when the Hα emission was generally weak. The top panel in each diagram shows the observed profiles,
while the bottom panel is a gray-scale representation of the profiles made through a linear interpolation in orbital phase. The thick line in Figure 4 depicts the Hα profile observed on HJD 2,451,466.6863, just 3 hr prior to the mid-point of the recent Chandra observation of high-resolution X-ray spectroscopy (Schulz et al. 2002). The emission was weak at that time, and the relatively low column density found by Schulz et al. (2002) probably results from the lower density in the wind at that epoch (or possibly from higher X-ray ionization of the wind; see \ref{section} 5).

Each diagram shows the orbital motion of the supergiant star as a backward S-curve in the gray-scale image, and there is clear evidence of this orbital motion in a blueshifted absorption and a redshifted emission feature (perhaps best seen in the weaker emission profiles in Figs. 4 and 5). This is the characteristic P Cygni–type shape that is the hallmark of mass loss in luminous stars (Lamers & Cassinelli 1999), and the association of this component with the wind of the supergiant in Cyg X-1 was demonstrated in earlier observations by Ninkov et al. (1987) and Sowers et al. (1998). The overall shape and intensity of the P Cygni component is comparable to that observed in other O-type supergiants (Ebbets 1982; Kaper et al. 1998).

The next striking feature in these diagrams is the appearance of large emission features in the wings of the profiles observed near the orbital conjunction phases, \( \phi = 0.0 \) and 0.5. These are most evident in the moderate and strong emission profiles (Figs. 3 and 2). Furthermore, we find that the central absorption component only appears at these conjunction phases in the strong emission case (Fig. 2). The light-curve solutions for Cyg X-1 (Gies & Bolton 1986a) indicate that the supergiant is close to filling its critical Roche surface, and in such a situation the wind is predicted to develop enhanced mass outflow in the directions opposite and especially toward the black hole companion (the focused stellar wind model of Friend & Castor 1982). We suggest that in the strong emission case the wind is substantially enhanced along the axis joining the stars and that at the conjunction phases we see the resulting emission with the largest values of projected radial velocity. These streams are also seen in partial projection against the disk of the star at the conjunctions (which creates the strong absorption seen then), while at other phases the emission is seen projected against the sky, resulting in an emission filling of the absorption core. The presence of clumps in the stream flowing toward the black hole may partially explain the temporal variations we observe and the prevalence of X-ray dips found near phase \( \phi = 0.0 \) (Bańcuńska-Church et al. 2000; Feng & Cui 2002).

All the sets of profiles show some evidence of very blueshifted absorption near and shortly following \( \phi = 0.5 \), supergiant superior conjunction. At this orientation we view the focused outflow in the foreground, and we suggest that the blueshifted absorption forms in the lower density, high-latitude part of the flow we see projected against the stellar disk, while the lower velocity blueshifted emission originates in the denser equatorial part of the flow that is mainly pro-
is the same in both the equatorial and our direction at injected against the sky. If we assume that the outflow velocity is the same in both the equatorial and our direction at \( \phi = 0.5 \), then the emission component radial velocity is equal to \( \sin i \) times the absorption component radial velocity (where \( i \) is the orbital inclination). For \( V_r(\text{abs}) = -380 \pm 50 \text{ km s}^{-1} \) and \( V_r(\text{em}) = -190 \pm 30 \text{ km s}^{-1} \), we derive an inclination of \( i = 30^\circ \pm 7^\circ \), which is consistent with the range of values derived from the light-curve analysis \( i = 28^\circ - 38^\circ \); Gies & Bolton 1986a) and with the best-fit model for the X-ray light curve \( i = 10^\circ - 40^\circ \); Wen et al. 1999). The assumption of equal outflow velocities in these two directions is probably not fully valid. For example, Friend & Castor (1982) find that the wind outflow is faster at high latitudes than in the high-density equatorial domain, so our estimate of the inclination is probably a lower limit.

The other important feature in the profile figures is the appearance of a blueshifted emission component near \( \phi = 0.25 \). This emission component was also found in earlier observations, and it could originate in the focused wind flow (Ninkov et al. 1987; Sowers et al. 1998) and/or in high-density gas near the black hole (Hutchings et al. 1974, 1979). In our earlier study of H\( \alpha \) (Sowers et al. 1998), we presented a simplified scheme to isolate this moving component of emission based on a Doppler tomography algorithm. The basic assumption is that each profile represents the sum of a spectral component that moves with the established radial velocity curve of the supergiant (the P Cygni component discussed above) and a second component that moves with a sinusoidal radial velocity curve parameterized by a semiamplitude \( K_{\text{em}} \) and an orbital phase of radial velocity maximum \( \phi_0 \). The tomography algorithm then uses an iterative corrections scheme (Bagnuolo et al. 1994) to reconstruct the spectral line profiles for each component. We performed tomographic reconstructions over a grid of possible \( K_{\text{em}} \) and \( \phi_0 \) values to find a solution that minimized the differences between the observed and reconstructed composite profiles. Since we now have nearly an order of magnitude more spectra than presented in Sowers et al. (1998), we have repeated this procedure with one key difference. We showed above that the conjunction phase profiles have shapes that are dominated by enhanced outflow along the axis joining the stars, and this part of the emission will appear broader at conjunctions than at other phases. Rather than introducing a third component with phase-variable width, we decided to include only the nonconjunction phase observations \( (\phi = 0.1-0.4 \text{ and } 0.6-0.9) \) in which the emission contributions from the axial outflow will be narrow and more concentrated toward the line center (reducing any confusion with the moving component seen blueshifted near \( \phi = 0.25 \)).

The results of our tomographic grid search for the parameters of the moving component are illustrated in Figure 6 in a plot of the rms residuals of the reconstruction fits. There are three regions in the parameter space that offer plausible solutions (and all make comparably good fits). We show the reconstructed profiles for each set of parameters in Figure 7. The first, and in our opinion most plausible, solution (marked “A”) occurs for \( \phi_0 = 0.79 \pm 0.04 \) and \( K_{\text{em}} = 218 \pm 30 \text{ km s}^{-1} \) (solid line). The reconstructed profiles show a well-developed P Cygni profile for the component moving with the supergiant, while the second component is a single emission peak that moves with a large but approximately antiphase motion (probably associated with gas near the black hole; see below). This radial velocity curve is shown as an S-curve in the gray-scale images of Figures 2–5.

A second solution (marked “B”) is found near \( \phi_0 = 0.81 \pm 0.06 \) and \( K_{\text{em}} = 56 \pm 30 \text{ km s}^{-1} \) (dotted line), and in this case the antiphase-moving component (right-
hand panel) is broader and double peaked. This is close to the solution advocated in Sowers et al. (1998; $\phi_0 = 0.86$ and $K_{em} = 68$ km s$^{-1}$), for which the Doppler shifts resemble those observed in the He $\Pi \lambda4686$ emission line (Gies & Bolton 1986b; Ninkov et al. 1987). Nevertheless, the adoption of this solution for the moving component in H$\alpha$ is problematic. First, the double-peaked structure of the reconstructed moving component suggests that it is a numerical artifact of a forced solution in which the slower moving emission is compensating for deeper blue absorption in the supergiant component. Second, the enhanced axial outflow discussed above is not treated in this simple two-component approach, and this emission will tend to favor low-velocity amplitude solutions (indeed, if the conjunction phase profiles are included in the reconstructions, this solution becomes more favorable). For both of these reasons, we believe this second, low-velocity solution is untenable.

The final solution (marked “C”) is another numerical artifact in which the moving component moves in phase with the supergiant but with a higher velocity ($\phi_0 = 0.23 \pm 0.05$ and $K_{em} = 185 \pm 50$ km s$^{-1}$; dashed line). In this case, the moving component is a complex absorption line that modulates a double-peaked emission profile for the supergiant. We can rule out this last solution since there is almost certainly no physical scenario consistent with such properties.

The simple, two-component model for the H$\alpha$ profiles suggests that the feature results from wind loss from the supergiant (the primary’s P Cygni profile) and gas emission with an antiphase radial velocity curve. We can use the derived kinematical parameters of the second component to explore its location in the system. The orbital geometry is sketched in Figure 8, in which we plot the system dimensions assuming that the supergiant is close to Roche filling (Gies & Bolton 1986a). The projected radial velocity vector derived for the moving component is the sum of an orbital velocity vector (dependent on location in the system) and a possible gas flow vector. The two simplest possibilities for these vector combinations are shown in the right-hand side of the diagram. In the first case, we assume that the emitting gas cloud is centered along the axis joining the stars and that a small vector component of gas flow from the supergiant to the black hole is responsible for the slight phase shift of the emission. This might correspond, for example, to high-density gas from the focused wind encountering the disk around the black hole. Then, the black hole will be situated close to or somewhat beyond this emission location, implying a mass ratio of $q = M_x/M_{opt} \leq K_{opt}/[K_{em} \sin(-\phi_0)]$. On the other hand, if we assume that the observed motion is entirely due to orbital motion, then the emission source is located slightly off axis, trailing the black hole. This could correspond to the location of a photoionization wake (Blondin et al. 1990) or a stream-disk interaction zone. The minimum disk radius estimate in the latter case would place the black hole at a position consistent with $q = K_{opt} \sin(-\phi_0)/K_{em}$. All these possibilities suggest $q \approx 0.36 \pm 0.05$, which is consistent with the range of mass ratios admitted by the light-curve solutions (Gies & Bolton 1986a) but which is lower than the estimate derived from
spectroscopic analysis of the supergiant by Herrero et al. (1995).

If the moving emission component does originate in gas accreted near the black hole, then it is important to determine how the emission flux varies as the wind of the supergiant varies. We illustrate in Figure 9 the reconstructed spectra of the supergiant and moving spectral components for the same four groupings of emission equivalent width shown earlier in Figures 2–5. We see that there is a reasonably good correlation between the strength of the supergiant P Cygni emission (related to the wind mass-loss rate) and the strength of the moving emission component (presumably related to the gas accreted by the black hole). We return to the issue of wind accretion in \S 5.

4. CORRELATED X-RAY VARIABILITY

The H$\alpha$ emission and associated stellar wind variations could be related to the X-ray flux variations since the wind is probably the main source of material accreted by the black hole. Here we investigate the temporal variations through a comparison of the H$\alpha$ equivalent width with the X-ray flux observed with the RXTE/ASM instrument\footnote{See http://xte.mit.edu.} (Levine et al. 1996). The ASM records the X-ray flux in three bands (1.5–3, 3–5, and 5–12 keV), and we begin by plotting the daily average of the low energy band flux with the H$\alpha$ equivalent width in Figure 10. Our first runs occurred during the low/hard X-ray state when the soft X-ray flux was small. However, the observations made near HJD 2,451,896 correspond to a time of X-ray flaring, while the DDO runs cover the recent, extended high/soft state of Cyg X-1. The general trend appears to be an anticorrelation

![Fig. 8. Diagram of the system geometry as viewed from above the orbital plane. The figure of the supergiant was calculated (ignoring radiation pressure) for a mass ratio $q = 0.36$ and a primary fill-out factor $\rho = 0.97$ (see Gies & Bolton 1986a). Orbital phases are listed around the periphery. The arrow at the stellar origin indicates the projected orbital velocity, while the center-of-mass position is indicated by “CM.” The projected velocity vectors at positions near the secondary show the observed semiamplitude $K_{\text{em}}$ of the antiphase-moving component and its derived orbital and flow components for two cases discussed in the text.](image1)

![Fig. 9.—Reconstructed spectra of the component moving with the supergiant (left) and the antiphase-moving component (right). The different plots correspond to samples for times of (top to bottom) strong emission (Fig. 2), moderate emission (Fig. 3), weak emission (Fig. 4), and the X-ray high/soft state (Fig. 5). The continua levels are each offset by 0.10.](image2)
between $W_{\lambda}(H\alpha)$ and the soft X-ray flux, and this same relationship is also found in some of the rapid variations. Figure 11 shows a detailed view of the covariations observed during the third run in 1999, this time depicting the higher time resolution, dwell-by-dwell, X-ray fluxes. The $H\alpha$ emission strength shows a general night-to-night trend, which was interrupted during one night (HJD 2,451,426.8), when the emission dropped significantly. We see that a small X-ray flare occurred at the same time as the $H\alpha$ decrease. Figure 12 shows an example of the reverse trend observed during our run with the best time coverage from 2000 December. Here we see that the local maximum in $H\alpha$ emission strength occurred at nearly the same time as a well-documented minimum in soft X-ray flux (HJD 2,451,898.6). There appear to be no obvious time lags between the $H\alpha$ and X-ray events, although our time resolution is limited by the near diurnal sampling of the $H\alpha$ observations.

We show the nature of the anticorrelation in all three X-ray bands in Figure 13. Here we have made a linear time
interpolation in the dwell-by-dwell X-ray fluxes in order to make the best approximation of the flux values at the specific times of the Hα observations. Note that the X-ray flux varies significantly on timescales shorter than the dwell-by-dwell sampling rate (median interval of ≈0.8 hr) and that the X-ray and optical observations are often noncontemporaneous, so that our time interpolation estimate of the X-ray flux may have large errors. The DDO observations made during the high/soft state are plotted as diamonds, while all the earlier measurements are shown as plus signs. These plots show that whenever we observed the Hα/C21 emission was weaker than this value, the X-ray flux was relatively low (especially in the lower energy bands). On the other hand, when the Hα emission was weaker than this value, the X-ray flux appeared to vary over a wide range nearly independent of $W_{\lambda}$. We show a spectral hardness ratio in Figure 14 that confirms the impression that the X-ray spectrum is generally harder when the Hα emission is stronger. These trends were first observed by Voloshina et al. (1997; based on data obtained during the 1996 high/soft state), and they also find confirmation in an important long-term monitoring program of Hα made at the Crimean Astrophysical Observatory (A. E. Tarasov 2002, private communication).

5. DISCUSSION

Our results indicate that X-ray flux appears to be related to the state of the wind (as observed in the Hα emission strength). When the Hα emission is strong the X-ray flux is consistently low, but when the emission is relatively weak, the X-ray flux can cover a wide range in values. There are three processes that can potentially explain these observations: (1) X-ray photoionization of the wind leading to a decrease in Hα emissivity, (2) wind-related changes in column density toward the X-ray source, and (3) variations in wind strength that result in changes in accretion rate. Here we argue that all three processes are required to help explain our results and that changes in the wind accretion rate may trigger the X-ray transitions in Cyg X-1.

The first possible explanation is that increased X-ray emission leads to heating of the wind and a corresponding decrease in Hα emissivity (Brocksopp et al. 1999a). Van Loon et al. (2001) show how the X-ray ionization of the wind in the low/hard state causes orbital variations in the ultraviolet P Cygni lines formed in the wind (e.g., the Hatchett-McCray effect; Hatchett & McCray 1977). The X-ray ionization effects become more severe in the high/soft state, and Wen et al. (1999) describe how the wind absorption effects decrease significantly in such highly ionized conditions. Hydrogen is expected to be nearly fully ionized in the base of the wind irrespective of the X-ray state, but if the gas is heated by an elevated soft X-ray flux, then the Hα emissivity will drop ($\propto T^{-1/2}$; Richards & Ratliff 1998).

The best evidence for ionization-related variability is the reduction in Hα equivalent width we observed during the miniflare of X-ray flux around HJD 2,451,426.8 (Fig. 11). The increase in soft X-ray flux and reduction in Hα occurred more or less simultaneously (within the time resolution of the data), as expected for the small light-travel time between the X-ray source and the facing hemisphere of the supergiant (≈54 s). On the other hand, the characteristic wind-crossing time between components is approximately 10 hr, and our data, although sparse in time coverage, do not indicate any time lag of this order between the Hα and X-ray variations. This event occurred near orbital phase $\phi = 0.77$, and the two spectra we obtained then show Hα profiles with unusually deep absorption cores (see Fig. 4) compared to observations on the preceding and following nights. At this orientation the wind between the stars was moving tangentially to our line of sight, and the emission from this region, if present, would have filled in the line core. However, if this inner region was significantly photoionized by the X-ray miniflare, then the residual emission in the line core would have vanished to produce the deeper absorption core. Thus, the timing and line properties of this event suggest that it was caused by X-ray photoionization.

On the other hand, there are several lines of evidence that X-ray photoionization is not the dominant cause of the Hα variations. First, we would expect the anticorrelation between Hα emission and X-ray flux to be better defined than exhibited in Figure 13 if X-ray photoionization drove the emission variations (although the scatter may be partly the result of the poor time resolution and poor overlap of the Hα and X-ray observations). There are several examples (especially during the X-ray low/hard state) where we observed large excursions in the Hα emission while the X-ray flux was essentially constant (Fig. 10). Second, if X-ray photoionization significantly altered the Hα emissivity of the gas above the hemisphere facing the X-ray source, then we should observe changes in the shape of the supergiant’s P Cygni component with orbital phase. The variations would be largest in the high/soft X-ray state, and would result in decreased blue absorption near $\phi = 0.5$ and decreased red emission near $\phi = 0.0$. The spectra observed in the high/soft X-ray state (Fig. 5) show that the predicted changes may be present but are relatively minor in nature. Third, we find evidence of large-scale variations in the Hα emission that forms in the X-ray shadow above the hemisphere facing away from the X-ray source where no X-ray photoionization should occur. This region in the wind is best isolated in the radial velocity distribution of the emission near orbital phase $\phi = 0.5$ when this back-side outflow is the dominant contributor to the redshifted peak of the
P Cygni profile. However, given the probable low orbital inclination, this part of the profile also includes some contributions from the X-ray–illuminated hemisphere. We show in Figure 15 the red peak emission height for spectra obtained near this phase plotted against X-ray flux. These diagrams show that the strength of the emission component from the X-ray shadow region is generally independent of the X-ray flux level in both the low/hard (+ signs) and high/soft (diamonds) X-ray states, as expected for an emitting region sheltered by the supergiant. In contrast, we show in Figure 16 the peak intensity of the blue emission peak isolated near orbital phase $\phi = 0.5$ vs. the time-interpolated dwell RXTE/ASM count rates. This part of the Hα emission forms in a region close to the black hole where X-ray photoionization does appear to affect the emission strength. The outlying points probably result from time interpolation of the X-ray flux in intervals when the optical and X-ray observations are noncontemporaneous.

Fig. 15.—Same as Fig. 13, but for residual intensities of the red peak of the Hα P Cygni profile for spectra obtained near orbital phase $\phi = 0.5$ vs. the time-interpolated dwell RXTE/ASM count rates. This part of the Hα emission forms in a region where X-rays are mostly blocked by the supergiant so that photoionization effects are minimized.

Fig. 16.—Same as Fig. 13, but for residual intensities of the blue peak of the Hα profile for spectra obtained near orbital phase $\phi = 0.25$ vs. the time-interpolated dwell RXTE/ASM count rates. This part of the Hα emission forms in a region close to the black hole where X-ray photoionization does appear to affect the emission strength. The outlying points probably result from time interpolation of the X-ray flux in intervals when the optical and X-ray observations are noncontemporaneous.

X-rays). We doubt that wind absorption plays a major role in explaining the general anticorrelation between Hα and X-ray emission because the scatter in their temporal variations (Fig. 13) is much larger than we would expect for a direct cause-and-effect relationship. Furthermore, the amplitude of the wind density fluctuations implied by the Hα changes is too small to explain the range in X-ray variability. Wen et al. (1999) show that the X-ray light curve can be explained by the changing column density of the line of sight to the black hole as we peer through different portions of the supergiant’s wind (strongest absorption at supergiant inferior conjunction, $\phi = 0.0$). Their ASM 1.5–3 keV orbital light curve for the low/hard state shows a 25% decrease at $\phi = 0.0$ relative to $\phi = 0.5$. Bałucinska-Church et al. (2000) also studied the variation in column density with orbital phase, and they suggest that the orbital modulation in X-ray flux corresponds to a fluctuation of 6–10 times in column density (depending on the assumed ionization of the wind). However, the observed variations in the emission strength generally indicate column density changes of a factor of less than 2 (see below). Wind column density changes of this order are too small to account for the large changes in X-ray flux. Thus, wind absorption variations are insuffi-
cient to explain the general anticorrelation between the H\(\alpha\) emission strength and X-ray flux. Nevertheless, we might expect the wind absorption processes to appear most prominent near the inferior conjunction of the supergiant, when the X-ray light curve attains a minimum and a peak occurs in the frequency of rapid X-ray dips (Wen et al. 1999; Bahucinska-Church et al. 2000; Feng & Cui 2002). It is noteworthy in this regard that the case of the simultaneous H\(\alpha\) maximum and X-ray flux minimum shown in Figure 12 did indeed occur near this phase (at \(\phi = 0.02\)).

If we ignore the effects of X-ray ionization on the H\(\alpha\) emissivity, then we can make an approximate estimate of how the wind mass-loss rate and density vary as a function of the H\(\alpha\) emission strength (Puls et al. 1996). Herrero et al. (1995) show predictions of how the H\(\alpha\) profile will vary as a function of mass-loss rate (see their Fig. 4), and we measured the equivalent widths of their profiles to calibrate the mass-loss rate as a function of H\(\alpha\) equivalent width (pro-rated to their final estimate of mass-loss rate for the time of their observations, \(3.0 \times 10^{-6}\) \(M_\odot\) yr\(^{-1}\)). The functional fit in this case is

\[
-M = (1.85 - 1.01 W_\lambda - 0.04 W_\lambda^2) \times 10^{-6} \, M_\odot \, \text{yr}^{-1}.
\]  

We grouped our equivalent width data according to the X-ray state at the time of observation (setting aside the results obtained near HJD 2,451,896 that may correspond to a “failed transition”), and the mean equivalent width for each group yields mass-loss rates of \((2.57 \pm 0.05) \times 10^{-6}\) and \((2.00 \pm 0.03) \times 10^{-6}\) \(M_\odot\) yr\(^{-1}\) for the low/hard and high/soft states, respectively (the quoted errors are based on the standard deviation of the mean and do not include the larger errors associated with the calibration of the \(W_\lambda\)–\(M\) relationship and with our neglect of the multiple component nature of the H\(\alpha\) emission). This suggests that the mass-loss rate is \(\approx 22\%\) lower during the rare high/soft state compared to the more common low/hard state. Since this calculation ignores the X-ray photoionization that may be more important in the high/soft state and since photoionization will decrease H\(\alpha\) emission strength, our estimate for the mass-loss rate during the high/soft state is best regarded as a lower limit. Nevertheless, the general decrease in wind strength during the high/soft state is also observed in the emission from the X-ray shadow region (Fig. 15) that should be relatively free from the effects of photoionization. We find that the mean residual emission intensity of the red peak near phase \(\phi = 0.5\) is \(0.139 \pm 0.008\) and \(0.114 \pm 0.006\) for the low/hard and high/soft states, respectively. Wen et al. (1999) also found that the wind mass-loss rate is lower in the high/soft state based on their analysis of the X-ray orbital light curve.

Taken at face value, our results present a paradox: the X-ray flux decreases when the wind mass-loss rate increases. We suggest that the resolution of this quandary lies in how the wind velocity changes with wind ionization state (originally proposed by Ho & Arons 1987 and developed in more physical terms by Stevens 1991). When the wind mass-loss rate is high, the wind density is also proportionally high, and therefore the X-ray ionization effects on the wind are confined to the region close to the black hole since the size of the surrounding ionized region depends on wind density as \(n^{-1}\) (Stevens 1991; van Loon et al. 2001). Most of the wind volume surrounding the star will contain the many important ions that propel the radiative driving of the wind so that it reaches a terminal velocity of approximately 2100 km s\(^{-1}\) (Herrero et al. 1995). However, the wind flow close to the black hole will become ionized, and these advanced ionization states will generally have transitions at frequencies much higher than the peak of the stellar flux distribution. Consequently, there are fewer absorbing transitions at frequencies where the stellar flux is concentrated and radiative driving of the wind becomes less effective. Stellar wind gas leaving the part of the supergiant facing the X-ray source will be accelerated by radiative driving, reaching a significant fraction of the terminal velocity before crossing the distant ionization boundary (Stevens 1991). Models of wind accretion by the black hole suggest that the mass accretion rate is proportional to \(M/v^4\) (Bondi & Hoyle 1944; Lamers, van den Heuvel, & Petterson 1976; Stevens 1991), and since the flow velocity \(v\) is relatively large, only modest mass accretion occurs. It is easy to imagine that some of the outflow from the supergiant to the black hole bypasses the black hole altogether, and absorption by the gas beyond the black hole could explain the presence of a secondary minimum in the low/hard state X-ray light curve at orbital phase \(\phi = 0.5\) (Karitskaya et al. 2001).

However, when the mass-loss rate drops, the X-ray ionization zone will become larger because of the reduced wind density. The dominant ions that provide the resonant transitions that in turn drive the stellar wind will disappear with increased ionization, and the wind outflow will experience only a modest acceleration and reach a speed of just a few hundred kilometers per second (before the flow dynamics become dominated by the gravitational acceleration of the black hole). This altered outflow will be denser and slower in the vicinity of the black hole, and since the accretion rate varies as \(M/v^4\), the overall accretion rate will increase significantly because of the slower outflow (and despite a real decline in \(M\)).

If this basic scenario is correct, then transitions from the low/hard to the high/soft state are triggered when the supergiant undergoes an episode of reduced mass loss. Stevens (1991) demonstrates that the decrease in the wind force multiplier occurs rather suddenly once a specific gas density is reached, and we would argue that this is the reason why the transitions are relatively fast and the X-ray states are bimodal. Once the transition occurs, the system tends to remain in the high/soft state because the increased accretion rate and associated larger X-ray fluxes make it easier to keep the wind in the highly ionized state (even with modest increases in mass-loss rate). The line of sight to the black hole then passes through mainly ionized gas all around the orbit, and the wind absorption of the X-ray flux decreases so much that the X-ray light-curve modulation vanishes (Wen et al. 1999). The increased mass accretion in this state causes the optically thick, geometrically thin (Keplerian) accretion disk to extend farther inward toward the black hole, producing more soft X-rays, while the coronal (ADAF or sub-Keplerian) region, which produces the bulk of the hard X-rays, becomes smaller, and thus the X-ray spectrum softens (Ebisawa, Titarchuk, & Chakrabarti 1996; Esin et al. 1998; Brocksopp et al. 1999a). The enhanced soft X-ray flux heats the accreting gas, which reduces the H\(\alpha\) emission from the accretion flow (Figs. 9 and 16). It is only once the supergiant can maintain a strong mass outflow that the wind becomes dense enough to reduce the ionization effects and to create the high speeds that then lower the mass accretion rate and force the system back to the low/hard state.
The long-term variations in the mass-loss rates of massive supergiant stars are not well documented, but there is circumstantial evidence of significant variations on timescales of years (Ebbets 1982; Markova 2002). Thus, we suggest that the high/soft states that occur every 5 years or so in Cyg X-1 correspond to quasi-cyclic minima in the mass-loss rate of the supergiant.

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