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RAPID VARIABILITY OF P CYGNI LINES IN MASSIVE X-RAY BINARIES

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ABSTRACT

In early-type X-ray binaries, the recombination time scales for ions such as C IV, Si IV, and N V in the stellar winds of their massive OB companion stars can be very short compared to typical X-ray pulsation or fluctuation time scales. Thus, we predict that the "bleached zones," in which these ions are removed from the stellar wind by X-ray photoionization, will track the X-ray beam as it rotates and that the P Cygni line profiles due to these ions will pulsate. With the *IUE* satellite we obtained low-resolution UV spectra of the binary X-ray system HD 77581/4U 0900−40 resolved into six phase bins of the 283^s pulse period; the observed upper limit to the pulse amplitude of the equivalent width of C IV λ1550 was less than the predicted value. However, the pulsations should be easy to observe with the Hubble Space Telescope.

Subject headings: line profiles — stars: wind — ultraviolet: spectra — X-rays: binaries

I. INTRODUCTION

Massive OB stars have strong stellar winds, manifested by the P Cygni lines in their ultraviolet spectra, e.g., C IV λ1550, N V λ1240, and Si IV λ1500. If such a star has a compact X-ray source in a close binary orbit, the X-ray source will photoionize the trace ions in the wind, causing the P Cygni lines to vary with the brightness and orbital phase of the X-ray source. This variability, predicted by Hatchett and McCray (1977), has been observed with the *IUE* satellite in several such systems (Hammerschlag-Hensberge 1980; Cordova and Howarth 1986). A detailed theoretical model for the orbital variation of the P Cygni line profiles in the system HD 77581/4U 0900−40 (McCray *et al.* 1984, hereafter paper I) agreed qualitatively with the observed effect.

In this paper we point out that the time scales for ions in strong stellar winds to readjust their abundances to the X-ray illumination are short compared to the typical pulsation and random fluctuation periods of the X-ray sources. Therefore, we can expect that the "bleached zone," in which, say, the C IV ion is removed from the wind by X-ray photoionization, should track the X-ray beam as it rotates or fluctuates. Consequently, we may predict that the P Cygni lines of such systems should vary on time scales of minutes or less. For several binary X-ray systems with early-type companion stars, this variability should be easy to observe with the Hubble Space Telescope. The analysis of such observations should provide a powerful method for inferring the properties of the X-ray beam and the dynamics of the stellar wind.

II. A MODEL FOR PULSATIONS OF THE P CYGNI LINES OF HD 77581/4U 0900−40

a) *The Model*

Here we illustrate the predicted effect with a model of the HD 77581/4U 0900−40 system, consisting of a B0.5 Ia supergiant and a binary X-ray pulsar with orbital period $8^d.96$ and pulse period $P = 283^s$ (Joss and Rappaport 1984). The parameters for the model are the same that we used in Paper I: stellar radius $R_* = 35\ R_\odot$, orbital radius 48 $R_\odot$, stellar wind mass-loss rate $\dot{M} = 4 \times 10^{-6}\ M_\odot\ \mathrm{yr}^{-1}$, and terminal velocity 1700 km s^{-1}. We assume that the stellar wind is stationary and has a spherically symmetric density and velocity structure, neglecting the (possibly substantial) effects of the X-ray source on the hydrodynamics of the wind. The electron density in the stellar wind is given approximately by $n_e(x) = 9.2 \times 10^9 x^{-2}(1 - x^{-1})^{-1}$ cm^{-3}, where $x = R/R_*$. Details of the assumed density profile and ionization state of trace elements in the stellar wind when not illuminated by the X-ray source are given in Paper I.

The main difference between the present model and that of Paper I is that there we approximated the X-ray source by an isotropic steady source, whereas here we represent the X-ray source with a rotating beam. We assume that the rotation axis of the pulsar is parallel to the orbital axis and that the orbital inclination is 90°.

The X-ray pulse profile tells us the intensity profile of the projection of this beam onto the observer's line of sight, but we must choose a model for its latitude dependence. We assume that the specific intensity is uniform within a cone beam of half-angle 45° centered on the rotational equator, and uniform with half the intensity elsewhere. The 2–10 keV luminosity per steradian within the cone is $L_x(\phi) = 1.6 \times 10^{35}$ ergs s^{-1} sr^{-1}. The pulse profile is assumed to be independent of photon energy for photon energy $h\nu < 10$ keV, and the spectrum is assumed to have the form $dL/d(h\nu) \propto \exp(-h\nu/10\ \mathrm{keV})$. These values agree very roughly with the 2–10 keV data of White, Swank, and Holt (1984), assuming a distance of 1.4 kpc. (We did not think that it was worthwhile to use a detailed model of the actual pulse profile, which is complex and changes substantially with photon energy.)

b) *Recombination Time Scales*

Here we point out that the abundances of trace ions in the stellar wind respond on very short time scales to changes in X-ray illumination. Consider, for example, C IV. Without X-ray illumination, the fraction of carbon in the ionization state C IV is given approximately by

$$g_{\rm C\,IV}^*(x) = 1.07 \times 10^{-2} x^{-2}(1 - x^{-1})$$

(most of the carbon is in the state C V). Now suppose that the X-ray beam ionizes all the C IV to C V or higher stages in some zone in the wind. Then, when the X-ray illumination ceases, the time scale for the C IV abundance to relax to its original value is given by $t_1 = g_{\rm C\,IV}^*(x)/[\alpha_{\rm C\,V} n_e(x)] = 0.28(1 - x^{-1})^2$ s. As this time scale is much less than the $283^{\rm s}$ pulse period throughout the stellar wind, we may infer that the fractional abundance of C IV adjusts almost instantaneously to the illumination by the X-ray beam. The same conclusion holds for Si IV.

The abundances of N V and O VI behave differently, because the dominant ions throughout most of the wind are N IV and O IV. Thus, throughout most of the stellar wind, X-ray illumination *increases* the abundances of N V and O VI (except very close to the X-ray source where the ionization level is even higher). When the X-ray illumination ceases, the abundances of these ions will decay with the recombination time scales; e.g., for N V,

$$t_r = [\alpha_{\rm N\,V} n_e(x)]^{-1} = 13.5x^2(1 - x^{-1})\ {\rm s}\ .$$

This is also less than the pulse period throughout a large volume of the stellar wind ($x < 4$), but not by such a large factor. Thus, we may infer that the abundances of N V and O VI will track the instantaneous X-ray illumination in the low-velocity part of the stellar wind near the star, but perhaps not at greater distances.

c) *Light-Travel Time Effects*

Characteristic light-travel time scales in the 4U 0900−40/HD 77581 system are not negligible compared to the $P = 283^{\rm s}$ pulse period: for example, the orbital radius is 112 lt-sec. Therefore, in order to properly describe the formation of P Cygni lines in this system, we must allow for the net light-travel time for the X-ray illumination to reach a given point in the stellar wind plus the time for a photon to travel from that point to a distant observer. To do this, we construct the surfaces in the stellar wind that a distant observer would perceive at one instant (in his frame of reference) to be illuminated by a sheet of rotating X-ray pencil beams emanating radially from fixed meridians of longitude on the neutron star surface. These surfaces are given by the equation

$$(\phi - \phi')\frac{Pc}{2\pi} = (r^2 + z^2)^{1/2} - r\cos\phi'\ , \qquad (1)$$

where r is the radial distance from the X-ray source projected onto the orbital plane, z is the height above the orbital plane, ϕ' is the longitude of a point in the stellar wind, and ϕ is the longitude of the meridian from which the pencil emanated ($\phi = 0$ when the pencil points at the observer). The intersections of these surfaces with the orbital plane are shown as the dashed curves in Figure 1 for X-ray source orbital phase 0.5 (superior conjunction). Near the X-ray sources these curves are spirals, and far from the X-ray source they asymptotically approach parabolae aimed at the observer with the X-ray source at the focus.

d) *X-ray Photoionization of the Stellar Wind*

We have calculated the ionization of trace elements in the stellar wind with a detailed photoionization code according to the procedure described in Paper I. Typical results (at superior conjunction) for C IV are illustrated in Figure 1. The inner and outer solid curves show the orbital plane projections of surfaces for which the Sobolev optical depth in the C IV λ1550 line is unity along lines of sight to the star, at pulse minimum and maximum, respectively. These curves correspond approximately to $g_{\rm C\,IV} = 1.8 \times 10^{-4}(1 - x^{-1})$. (The zone in which the X-rays heat the stellar wind to coronal temperatures has a scale size about 4 times smaller.)

Therefore, the "bleached zone," in which C IV absorption is missing as a result of X-ray photoionization, may be represent-

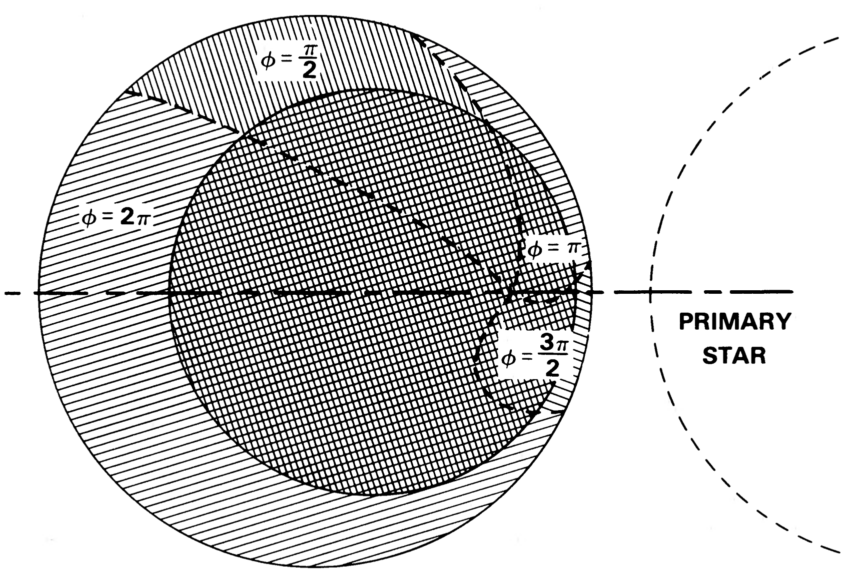

FIG. 1.—"Bleached zones" in the stellar wind of HD 77581, in which the C IV λ1550 resonance line is rendered transparent owing to photoionization of C IV by a rotating X-ray beam. Within the cross-hatched zone the C IV is removed by photoionization at pulse minimum. Within the outer solid curve the C IV is removed at pulse maximum. Dashed curves indicate shapes of surfaces illuminated by a rotating pencil beam at one instant as perceived by a distant observer. The alternately hatched zones indicate the shapes of the moving bleached zones at pulse phases $\phi = \pi/2, \pi, 3\pi/2, 2\pi$, respectively.

ed roughly by a time-independent zone (*crosshatched*) bounded by the inner solid curve plus a moving sector bounded by the inner and outer solid curves and a pair of moving dashed curves that assume the shapes of the dashed curves shown in Figure 1 at discrete pulse phases. This moving bleached zone (shown as alternately hatched zones for pulse phases $\phi = \pi/2$, π, $3\pi/2$, 2π) is responsible for the variability in the C IV resonance line. At superior conjunction the variability shows up only in the blueshifted absorption part of the P Cygni line, at Doppler shifts corresponding to projected stellar wind velocities at the location of the bleached zone. The shapes of surfaces of constant projected stellar wind velocities are illustrated in Paper I.

e) Pulsation of P Cygni Lines

We have calculated the P Cygni line profiles at superior conjunction and various pulse phases according to the procedure described in Paper I. The results for C IV λ1550 are shown in Figure 2. Also shown there is the line profile expected during X-ray eclipse. At all pulse phases the absorption trough is not as deep as that at X-ray eclipse because of the permanently bleached zone. The rotating bleached zone shows up as a "transparency feature" in the absorption-line profile that oscillates in velocity space as the X-ray beam rotates. This features reaches maximum blueshift at pulse phase $\phi = 2\pi$ (X-ray beam pointed at observer) and moves toward the red as the bleached zone rotates toward the star, where the projected wind velocity is less. Light-travel time delays introduce a marked asymmetry in the phase dependence of the line profiles; for example, the line profile at $\phi = 3\pi/2$ is very different from the profile at $\phi = \pi/2$, and more like that at $\phi = \pi$. Note that the equivalent width of the entire trough of the P Cygni line (indicated in Fig. 2) varies with pulse phase with a half-amplitude of about 0.37 Å.

We have also calculated the pulse-phase dependence of the Si IV λ1400 and N V λ1240 line profiles according to the same procedure. As was the case in Paper I, Si IV λ1400 behaves similarly to C IV λ1550. However, N V λ1240 behaves differently from C IV λ1550 and Si IV λ1400 because X-ray photoionization adds N V ions throughout most of the stellar wind, whereas it removes C IV and Si IV ions. Thus we predict that the rotating X-ray beam should introduce an extra opacity feature that oscillates in velocity space within the N V absorption trough.

III. *IUE* OBSERVATIONS

We attempted to observe this effect in HD 77581 with the *IUE* satellite by repeatedly trailing the stellar spectrum perpendicular to the long axis of the large slit of the SWP camera modulo the 283^s pulse period according to the procedure described by Payne and Coe (1986). The observations were made on 1986 July 11, from 1208 to 1822 UT, corresponding to X-ray orbital phase 0.48 to 0.51. Nearly optimum exposures at $\sim$1550 Å were obtained with three trails at a rate $0''.08\ s^{-1}$ or with five trails at $0''.125\ s^{-1}$, resulting in total exposure times of 750^s and 800^s, respectively. We obtained nearly full pulse-phase coverage twice with two exposures of the former type, initiated at different pulse phases, and once more with two of the latter type. With six independent pseudoorders along the slit, we were able to divide the slow trails into six pulse-phase bins of 60° and the fast trails into 10 pulse-phase bins of 36°.

Our spectra clearly show the N V λ1240, Si IV λ1400, and C IV λ1550 P Cygni lines. The spectral resolution of *IUE* in the low-resolution mode (approximately 6 Å at 1500 Å) was not adequate to observe the line profiles, but we were able to search for variability in the equivalent width of the absorption profile. Figure 3 shows our data in the vicinity of C IV λ1550. There is no evident variation above the noise level in the C IV

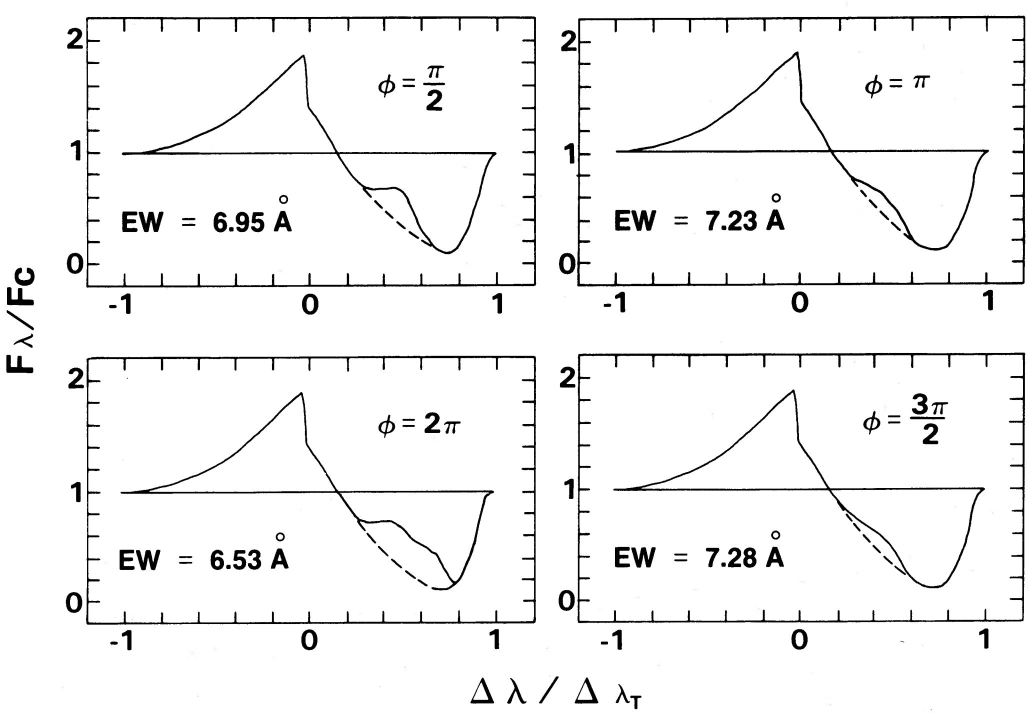

FIG. 2.—Predicted P Cygni profiles corresponding to X-ray pulse phases $\phi = \pi/2$, π, $3\pi/2$, 2π, respectively, for the C IV λ1550 resonance line in HD 77581, at X-ray source superior conjunction. In each case the predicted P Cygni profile is compared to the predicted profile during X-ray eclipse, and the equivalent width (Å) of the absorption part of the line profile is noted.

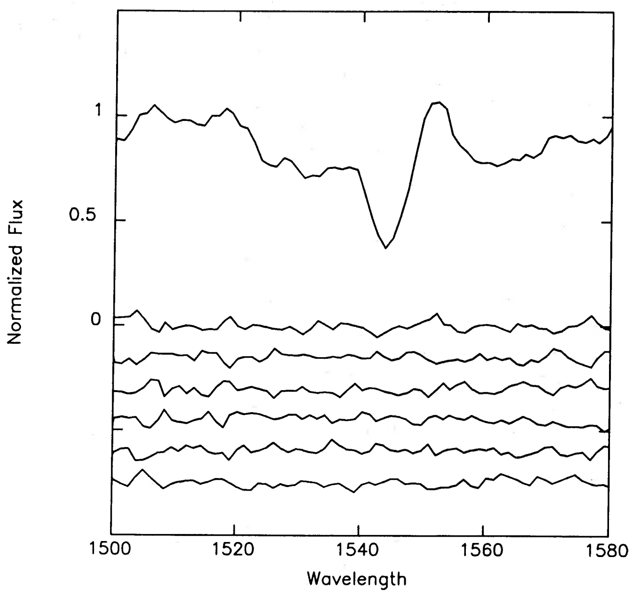

FIG. 3.—Time-resolved spectrum of HD 77581 in the vicinity of C IV λ1550 taken with the *IUE* SWP camera. The upper curve shows the pulse-phase averaged spectrum, normalized so that the estimated continuum count rate is 1.0. Each of the six curves below (with displaced zeros but the same normalization) represents the difference of the upper spectrum and a stacked spectrum corresponding to one of the 60° pulse-phase bins of the 283^s X-ray pulsation period. The pulse phase advances in 60° increments downward.

absorption feature at 1542–1548 Å. Clearly, much of the structure in the time-averaged spectrum is greater than the noise level and represents real features which appear to be stationary.

In order to estimate the statistical significance of our results, we measured an empirical pulse-phase variance of the equivalent width of the signal by sampling several adjacent 6 Å continuum bands; we attribute the resulting variance of 0.065 Å to noise. The observed pulse-phase variance of the equivalent width of the 1542–1548 Å absorption trough was 0.084 Å, a value of low statistical significance. However, our theory predicts that the pulse-phase variance of the equivalent width this feature should be 0.26 Å, a value greater than either the noise level or the measured variance of the absorption trough. In order to assess the significance of this difference, we constructed a probability distribution for the expected variance of the equivalent width of the absorption trough by convolving an assumed actual sinusoidal variation with a variance of 0.26 Å with a random signal with a variance of 0.065 Å. The probability that the resulting distribution (which is not Gaussian) would yield an empirical variance less than or equal to 0.084 Å is ~5%. Thus we estimate with ~95% confidence that our detected signal is due to an actual variability that is less than the theoretically predicted value.

Likewise, we have analyzed the entire SWP spectrum from 1200 to 2000 Å, and we see no significant evidence for pulse-phase variation in the continuum or in any spectral line.

IV. DISCUSSION

Our failure to detect pulsation in the lines has several possible explanations; we believe the most likely ones are that the X-ray source was in a low state or that the pulse amplitude of the soft X-rays (which dominate the photoionization of the stellar wind) is somewhat less than the amplitude we assumed in our model.

Of course, we do not expect the P Cygni line profiles in the 4U 0900−40/HD 77581 system to behave exactly as we have predicted. Our model contains idealized assumptions about the structure of the stellar wind and the X-ray beam that have no grounds other than expediency. However, we believe that we have shown that pulsations are likely to be observed in the P Cygni lines of this system and that we have correctly predicted the qualitative behavior of the effect.

It should be easy to observe pulsations in the P Cygni line profiles of HD 77581 at high spectral resolution in a short observation with the Faint Object Spectrograph on the Hubble Space Telescope (HST), even if they have an amplitude of only a few percent of the predicted value. Indeed, the HST can investigate periodic and aperiodic variability of P Cygni lines, not only in HD 77581, but also in other early-type binary X-ray pulsars, such as SMC X-1 and LMC X-4.

Such observations would tell us a great deal about the nature of the X-ray sources and the gas flows in these binary systems. For example, shocks and wakes may occur in the stellar wind due to the gravitation and radiation of the X-ray source, and these structures should show up as pulsating features in the UV resonance lines. By observing how the Doppler shifts and pulse phases of these features change with orbital phase, it should be possible to infer the spatial geometry of these structures. For example, they should show up as absorption features only if they occult the star. We may also be able to infer the X-ray beam shape from the detailed behavior of the pulsating P Cygni lines.

Finally, we remark that the rapid aperiodic variability of the X-rays from the black hole system Cygnus X-1 should echo in the P Cygni lines of its companion star HDE 226868 (Treves *et al.* 1980). However, the time delays resulting from light-travel times and the recombination time scales of the relevant ions should act as low pass filters that quench the most rapid variability in the UV resonance lines, depending on the location of the ions and the electron density in the stellar wind. Thus, observations of rapid aperiodic variability in the UV resonance lines of Cyg X-1 can tell us much about the interaction of that X-ray source with the wind of its companion star.

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