

A SPECTROSCOPIC SEARCH FOR COLLIDING STELLAR WINDS IN O-TYPE CLOSE BINARY SYSTEMS. III. 29 UW CANIS MAJORIS

MICHAEL S. WIGGS¹ AND DOUGLAS R. GIES

Department of Physics and Astronomy, Georgia State University, Atlanta, GA 30303-3083

Received 1991 September 23; accepted 1992 October 6

ABSTRACT

We have investigated the orbital-phase variations in the optical emission lines and UV P Cygni lines of the massive O-type binary 29 UW Canis Majoris to search for evidence of colliding winds. We present high signal-to-noise ratio spectra of the H α and He I λ 6678 emission lines and give radial velocity curves for several features associated with the photosphere of the more luminous primary star. The H α feature consists of a P Cygni component that shares the motion of the primary, and which probably originates at the base of its wind, and a broad, stationary emission component. We propose that the broad emission forms in a plane midway between the stars where the winds collide. Using a simple geometric model, we show that this placement of the broad component can explain (1) the lack of orbital velocity shifts, (2) the near-constancy of the emission strength throughout the orbit, (3) the large velocities associated with the H α wings, and (4) the constancy of the velocity range observed. On the other hand, the phase variations of the UV P Cygni lines (Si IV λ 1400, N V λ 1240, C IV λ 1550) appear to be more influenced by the primary's wind. The red peaks follow the motion of the primary, but with a smaller semi-amplitude due to a focusing of the primary's wind toward the secondary and/or line blending with emission from the secondary's wind. The Si IV λ 1400 red peak has maxima at the conjunctions which may result from the presence of the bow shock and an enhanced gas density between the stars. The blue edge of the P Cygni absorption troughs displays orbital-phase variations in velocity which we suggest reflect differences in turbulence in the wind in directions toward and away from the secondary. However, the shortward limit of the zero-intensity core of the line C IV λ 1550 (which we take as representative of the wind terminal velocity) shows no orbital variations. Because of the dominance of the primary's wind, a bow shock wrapped around the secondary might be expected, but we show that a planar bow shock between the stars is not inconsistent with the UV observations.

Subject headings: stars: early-type — stars: individual (29 Canis Majoris) — stars: mass loss

1. INTRODUCTION

In close binary systems of O-type stars, the individual stellar winds will collide between the stars to form shock fronts (Luo, McCray, & Mac Low 1990; Kallrath 1991; Stevens, Blondin, & Pollock 1992). The presence of the shock region can be detected through excess X-ray emission (Chlebowski & Garmann 1991) and orbital phase-related variations in the UV P Cygni wind lines (Shore & Brown 1988; Stevens 1993) and optical emission lines (formed in high-density regions in the circumstellar gas). This is the third paper in a series on the orbital-phase variations in the optical emission and UV wind lines of close O-type binaries. In Paper I (Gies & Wiggs 1991) we presented observations and a model of the circumstellar gas in the short-period system AO Cas (O9.5 III + O8 V; Bagnuolo & Gies 1991). Based on the radial velocity characteristics of the UV wind lines and the H α residual-emission properties, we proposed a model in which the winds collide and form a bow shock wrapped around the O8 V secondary. In Paper II (Wiggs & Gies 1992) we examined the massive binary system Plaskett's star (O7.5 I + O6 I; Bagnuolo, Gies, & Wiggs 1992b). In this system, the O6 I secondary star (less prominent in the spectrum) has the dominant stellar wind, and we found that the emission and wind line variations could be explained in a model where a wide bow shock surrounds the primary star and experiences a Coriolis deflection of $\approx 50^\circ$.

Here we examine the massive binary 29 UW Canis Majoris (HR 2781; HD 57060). Its spectrum has been variously classified as O7 Ia:fp (Walborn 1973), O8.5 If (Conti & Leep 1974), and O8 Iaf + O (Hutchings 1977). Stickland (1989) has reevaluated the orbital parameters using velocity data from *IUE* archival spectra, and by combining his results with velocities determined from studies in the optical, he obtained a nonzero eccentricity, $e = 0.118 \pm 0.009$, which is large for such a short-period binary (4.3934 days). The eccentric orbital solution is not supported by studies of the photometric light curve. The light curve shows a continuous variation associated with tidally distorted stars that undergo partial eclipses (Leung & Schneider 1978; Eaton 1978), and the minima are separated by exactly half a cycle as expected for a circular orbit. Leung & Schneider argue that the effects of Roche distortion, reflection, and eclipses conspire to make the observed radial velocity curve appear noncircular. Analysis of the light curves indicates that the secondary is somewhat cooler than the primary (Leung & Schneider 1978; Eaton 1978), but the evidence from spectroscopic studies is mixed. Struve et al. (1958) reported observing the secondary (or possibly a gas stream) in the He I λ 5876 line only during orbital phases when the secondary has a negative velocity. Hutchings (1977) found traces of a weak secondary spectrum in several line species, and from the velocity curves of these lines he obtained a mass ratio of $q = M_2/M_1 = 1.3 \pm 0.2$. The light curve admits a range in mass ratio between 0.75 and 1.3 and a range in inclination between 68° and 70° (Leung & Schneider 1978).

Single stars with a classification like that of the primary have

¹ Present address: Space Telescope Science Institute, SCARS Division, 3700 San Martin Drive, Baltimore, MD 21218.

well-developed stellar winds (Howarth & Prinja 1989), and thus we might expect to observe a collision between winds or between the wind of the primary and the surface of the secondary. The system does not show enhanced X-ray emission, but the absence of excess high-temperature gas may be due to the close proximity of the stars and lower wind velocities at the shock front (Chlebowski & Garmann 1991). However, it is clear that the primary does possess a strong wind. Drechsel et al. (1981) made *Copernicus* observations of the C III $\lambda 1175$ P Cygni line and found that the radial velocity curve of the profile follows that of the primary. They concluded that the mass outflow originates with the primary. Drechsel et al. also observed phase-related variations in the shape of the C III $\lambda 1175$ profile which they attributed to eclipse effects. Heap (1982) presented *IUE* spectra of 29 CMa for several important wind lines, and, based on the observed orbital-phase variations, she argued that the primary's wind is anisotropic with enhanced mass loss near the inner and outer Lagrangian points. She also suggested that a variation in the blue-edge velocity of the P Cygni troughs could be due to an ionization cavity between the stars. A larger set of *IUE* spectra was subsequently analyzed by Corcoran & Heap (1989). They also find that the blue edge of the P Cygni absorption troughs vary with orbital phase, but they argue that the cause is the orbital motion of the primary star. They note that the Si IV $\lambda 1400$ P Cygni emission peak shows pronounced maxima at the conjunction phases which could result from the removal of scattering ions in a shadow zone behind the secondary. Finally, there is evidence of a dense circumstellar gas component which produces strong emission lines at H α (Struve et al. 1958) and He II $\lambda 4686$ (Hutchings 1977).

In this paper we present high-quality optical spectra of the H α and He I $\lambda 6678$ emission profiles obtained over nine consecutive nights. In § 2 we give a qualitative description of the orbital phase-related changes observed in these lines, and we present radial velocity curves of several features. The orbital-phase variations in the UV stellar wind lines from archival *IUE* high-dispersion spectra are described in § 3. The optical and UV data suggest the existence of a bow shock between the stars, and in § 4 we discuss the possible geometry of the stellar wind in this system.

2. OPTICAL SPECTRAL VARIATIONS

The optical spectra were obtained between 1986 January 17 and 25 at the University of Texas McDonald Observatory using the 2.1 m telescope and coudé spectrograph. One additional spectrum was obtained nearly 2 years later (1987 December 29) to check on the repeatability of the orbital phase-related variations. During the first week (and for the 1987 observation) the spectra were made using a 600 grooves mm^{-1} grating (blazed at 8700 Å) in first order with an OG515 filter to block higher orders. These observations record the spectrum over the wavelength range 6500–6710 Å, and they have a spectral resolution of 0.56 Å FWHM (4.0 pixels). During the second week the setup was changed to a 1200 groove mm^{-1} grating (blazed at 6000 Å) in first order. The spectrograph slit was widened to obtain the same spectral resolution of 0.56 Å FWHM (8.3 pixels), and two exposures were made to record H α (6512–6614 Å) and He I $\lambda 6678$ (6627–6729 Å). The detector was a Reticon (RL1728H/20) consisting of a linear array of 1728 $15 \times 750 \mu\text{m}$ pixels. A S/N of 400 per pixel in the continuum was generally obtained in exposure times of 15–40 minutes.

TABLE 1
RADIAL VELOCITIES FROM OPTICAL SPECTRA

ORBITAL PHASE	HJD (2,440,000 +)	V_r (km s $^{-1}$)			
		He I $\lambda 6678$	He II $\lambda 6527$	He II $\lambda 6683$	Si IV $\lambda 6701$
0.004.....	6447.828	124.8	165.9	240.8	217.0
0.128.....	6452.767	–60.6	–43.1	–20.5	12.8
0.242.....	6448.874	–174.5	–165.2	–154.7	–157.5
0.354.....	6453.762	–213.5	–184.4	–179.5	–234.5
0.454.....	6449.806	–160.8	–141.0	–115.9	–195.2
0.588.....	6454.788	...	12.2	...	...
0.592.....	6454.808	–2.1	...	8.3	–9.7
0.683.....	6450.813	72.2	149.2	172.3	141.0
0.815.....	6455.787	...	246.8	...	...
0.832.....	6455.860	180.5	...	239.4	243.3
0.841.....	7158.847	...	267.8	280.3	258.3
0.910.....	6451.809	204.9	259.3	319.1	234.8

A journal of observations is presented in Table 1, which lists the Heliocentric Julian Dates of midobservation. The phases were calculated from the 4.393411 day period given by Stickland (1989). Stickland fitted radial velocity data from *IUE* spectra to obtain an orbital solution using a somewhat less precise period (4.3934 days), so we applied the better period together with Stickland's velocities and orbital parameters to solve for the time of periastron passage alone, $T = 2,443,719.5030$ (which defines $\phi = 0.0$), using the program of Morbey & Brosterhus (1974). According to this elliptical orbit ($e = 0.129$), primary superior conjunction occurs at $\phi = 0.083$. However, a different phase is found using photometric data (Stickland 1989). Using our ephemeris from the elliptical orbit, primary superior conjunction occurs at $\phi = 0.129, 0.126$, and 0.136 based on the photometric analyses of Ogata & Huku-saku (1977), Leung & Schneider (1978), and Eaton (1978), respectively. Since the reality of the eccentricity is open to question (Leung & Schneider 1978), we will assume that primary superior conjunction occurs at $\phi = 0.13$ as indicated by the photometric solutions.

The spectra were reduced by standard techniques which included the removal of atmospheric telluric lines (see Paper I). The final step yields rectified spectra transformed to a uniform heliocentric wavelength grid. The resulting spectra are plotted in Figures 1 and 2 as a function of radial velocity assuming rest wavelengths of 6562.682 and 6678.148 Å for H α and He I, respectively. The spectra are placed in the upper portion of each diagram so that their continua are aligned with the orbital phase of observation. The bar at the upper right indicates the intensity scale relative to the continuum. The lower portion of the figure shows the same spectra portrayed as a gray-scale image in which spectral intensity is transformed into a gray-scale intensity (dark in the absorption cores and bright at the emission peaks). The spectrum at each orbital phase in the image was calculated by a linear interpolation between observations with the closest phases.

We begin with those lines which show the "s" pattern corresponding to the velocity curve of the primary. These include the absorption lines He I $\lambda 6678$ and He II $\lambda\lambda 6527.13, 6683.20$ and the emission lines Si IV $\lambda\lambda 6667.56, 6701.21$ (Fullerton 1989). All of these lines are typically found in mid-O supergiants (Conti 1974; Ninkov, Walker, & Yang 1987a; Ninkov et al. 1987b). The weak emission line at $\lambda 6610$ which is seen in the spectrum of Plaskett's star (Paper II) is absent from our spectra

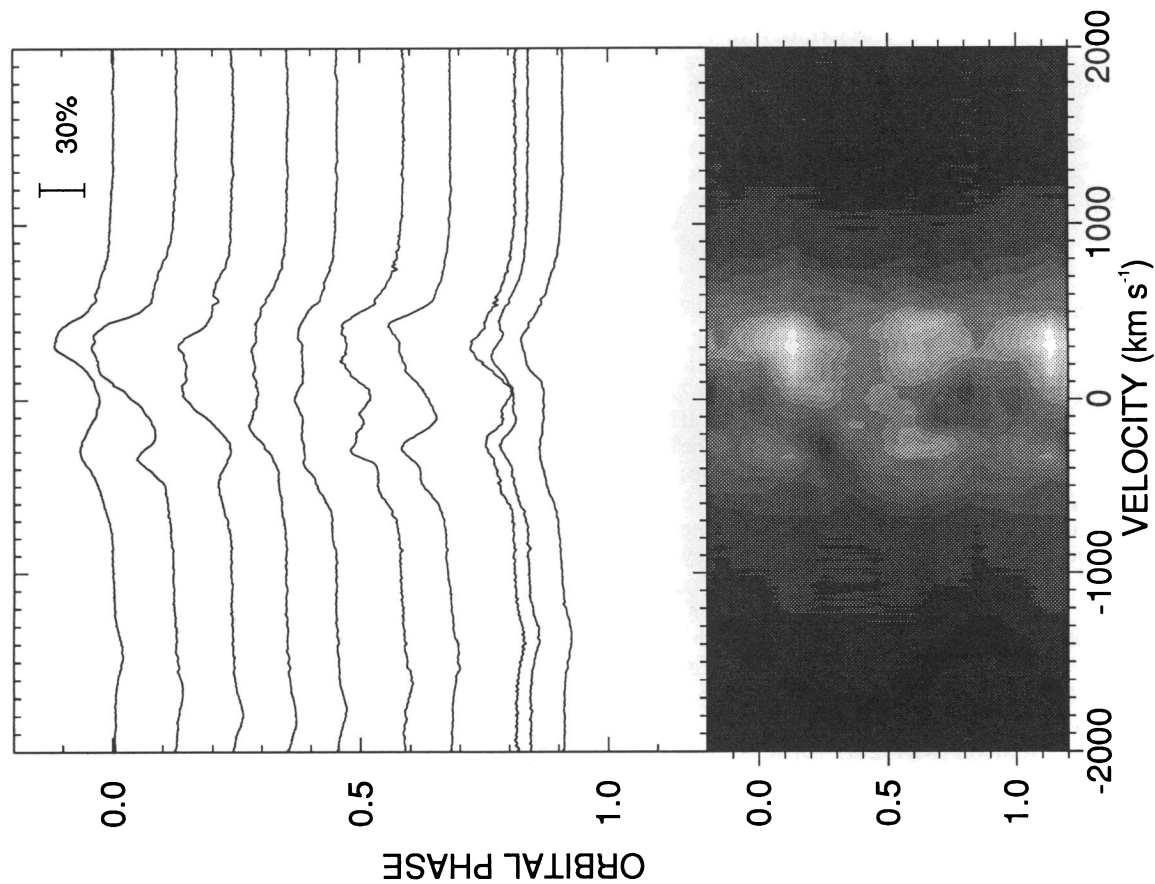


FIG. 1

FIG. 1.—*Upper panel:* H α line profiles plotted against heliocentric radial velocity. The profiles are arranged in order of increasing orbital phase, and each spectrum is placed in the y-ordinate so that the continuum equals the phase of observation (phase 0.0 = periastron passage). The bar at the upper right gives the spectrum intensity scale relative to a unit continuum. The next to last spectrum was obtained 2 years after the other spectra. *Lower panel:* Gray-scale representation of the profile variations shown above. Here each spectral intensity is assigned one of 16 gray levels based on its value between the minimum (deepest absorption) and maximum (highest emission) observed values. The spectrum at each phase in the image is calculated by a linear interpolation between the closest observed phases. The spectral image for the first and last 20% of the orbit are reproduced at the bottom and top of the image, respectively, to improve the sense of phase continuity.

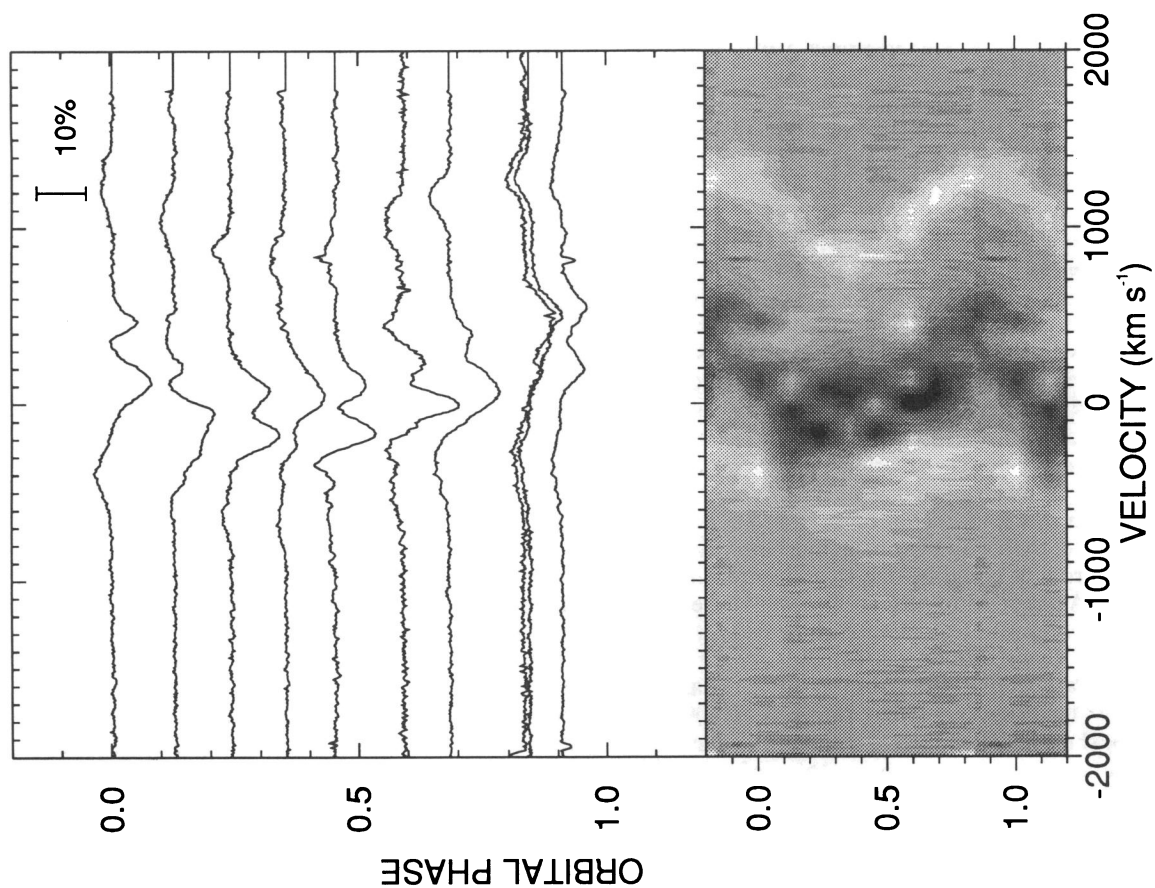


FIG. 2

FIG. 2.—He I 46678 profiles in the same format as in Fig. 1

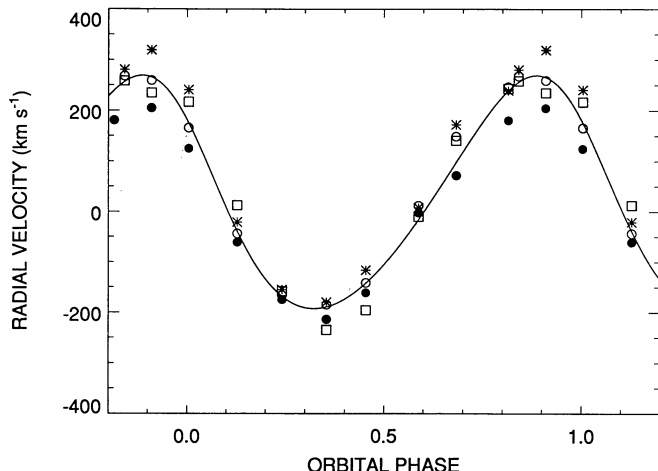


FIG. 3.—Radial velocity curves for the various lines in the optical spectra. The symbols are as follows: filled circles: He I 6678; open circles: He II 6527; asterisks: He II 6683; squares: Si IV 6701. The velocity errors are comparable to the symbol sizes.

of 29 CMa. There are no spectral features attributable to the secondary component readily seen in these spectra. We measured radial velocities for all of these features (except Si IV 6667, which is too contaminated by emission from He I 66678) by fitting parabolas to the lower (upper) third of the absorption (emission) profiles (Table 1). The error in individual measurements ranges between 2 and 9 km s⁻¹ depending on the width and intensity of the feature. The measured velocities and the eccentric orbital solution from Stickland (1989) are plotted against orbital phase in Figure 3. The close agreement between the velocities and orbital solution clearly indicates that these lines are associated with the photosphere of the primary.

Orbital solutions for the velocity curves of each line were calculated using the program of Morbey & Brosterhus (1974), assuming Stickland's period. The fitted parameters— γ , the systemic velocity; K_1 , the velocity amplitude; e , the orbital eccentricity; ω , the longitude of periastron; and T , the date of periastron passage (plus the rms residual from the fit σ)—are listed in Table 2. We regard the results for He II 6527 and Si IV 6701 as the most reliable, since the other two features are distorted by emission associated with He I 66678. The derived elements are consistent with the published results described by Stickland (1989). However, although our derived eccentricity is consistent with previous results, its value is only weakly constrained by the present data. According to the statistical criterion of Lucy & Sweeney (1971), the fits provided by elliptical orbits are not significantly better than those provided by circular fits, so we cannot verify the reality of a nonzero eccentricity.

Next, we turn our attention to the strong H α emission line (Fig. 1). This feature is nearly stationary in velocity but it displays a substructure that varies coherently with orbital phase.

The repeatability of the orbital phase-related changes is demonstrated by the similarity of the two line profiles near $\phi \approx 0.8$ which were obtained nearly 2 years apart. The phase-related changes are probably repeatable over time scales of decades, since the appearance of the gray-scale image in Figure 1 is very similar to the spectra from 1957–1958 that are displayed in Struve et al. (1958). The emission intensity has maxima near the two conjunction phases, $\phi = 0.13$ and 0.63. These phases also correspond to the minima in the continuum light curve, and since all our spectra are rectified to the continuum, some apparent emission strengthening might be expected because of the change in the ratio of constant emission to decreased continuum flux. To remove this source of intensity variability from the profiles, we have transformed the spectra to a constant flux representation using the relation

$$F'_\lambda(\phi) = I(\phi)[F_\lambda(\phi) - 1], \quad (1)$$

where I is the phase-dependent intensity (normalized to 1.0 at quadrature phases) and F'_λ and F_λ are the transformed and original spectra, respectively. We used the Johnson V photometric light curve of van Genderen et al. (1988), which we transformed to a linear intensity scale to represent the light variations. We made a linear interpolation in orbital phase to their photometry and then smoothed the resulting curve using a Fourier filter (Brault & White 1971). The constant flux representation of the spectra is illustrated in Figure 4. An intensity maximum at primary superior conjunction $\phi = 0.13$ is still seen, but the profiles now have a more uniform intensity appearance. The average of the 10 transformed spectra has an equivalent width of $-5.25 \text{ \AA}$ (much larger than observed in single O stars [Ebbets 1982] or expected from normal winds [Drew 1990]) and a full width at half-maximum of 1050 km s⁻¹ with wings extending to $\pm 1100 \text{ km s}^{-1}$.

The overall structure of the H α line can be divided into three components. First, there is a broad emission plateau that maintains an approximately constant intensity throughout the orbit and displays few or no velocity excursions (demonstrated by the nearly vertical intensity contours of the high-velocity wings in Fig. 4). Superposed on this plateau is a P Cygni component (blueshifted absorption plus redshifted emission) that follows approximately the motion of the primary. The absorption core disappears between orbital phases 0.4 and 0.6. Struve et al. (1958) found this same behavior in their H α spectra, and they attempted to construct a velocity curve for the absorption core (something we have not done because of the ill-defined nature of the minimum). Our spectra appear to be consistent with the Struve et al. measurements (shown in Fig. 1 of their paper), which have a very negative systemic velocity of $\gamma \approx -190 \text{ km s}^{-1}$ and a somewhat small semi-amplitude $K_1 \approx 190 \text{ km s}^{-1}$. The third component is a local emission enhancement ($\approx 35\%$) that occurs near $\phi = 0.1$ and $V_r = 300 \text{ km s}^{-1}$. We will discuss the possible origins of these components in § 4.

TABLE 2
ORBITAL SOLUTIONS FROM OPTICAL LINES

Line	γ (km s ⁻¹)	K_1 (km s ⁻¹)	e	ω	T (HJD - 2,440,000)	σ (km s ⁻¹)
He I 6678	-8.4 ± 3.2	205.5 ± 4.4	0.089 ± 0.023	$86^\circ \pm 2^\circ$	6452.591 ± 0.022	13.6
He II 6527	28.9 ± 4.1	232.0 ± 4.1	0.071 ± 0.019	60 ± 15	6452.249 ± 0.180	9.5
He II 6683	49.4 ± 8.7	244.9 ± 11.7	0.166 ± 0.051	78 ± 7	6452.523 ± 0.081	28.4
Si IV 6701	23.1 ± 5.4	249.8 ± 7.4	0.064 ± 0.030	158 ± 29	6453.553 ± 0.347	16.8

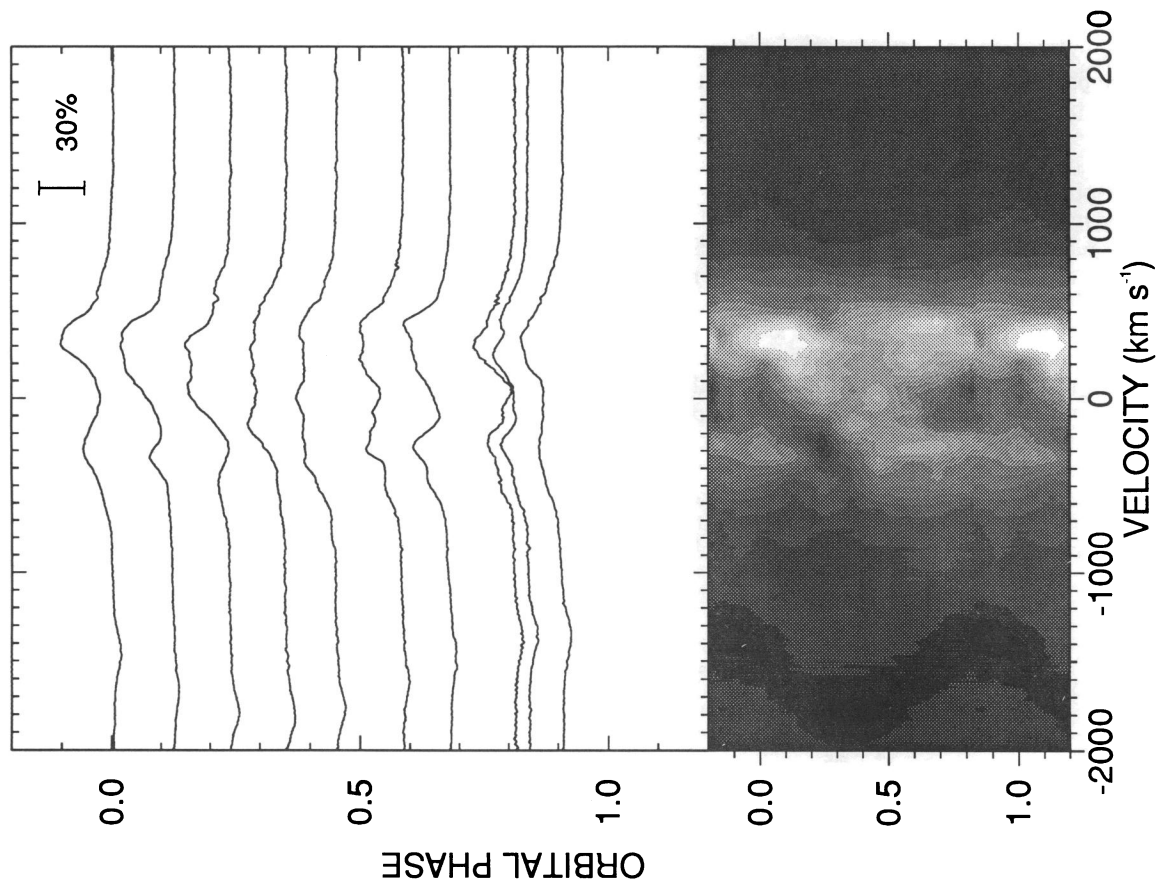
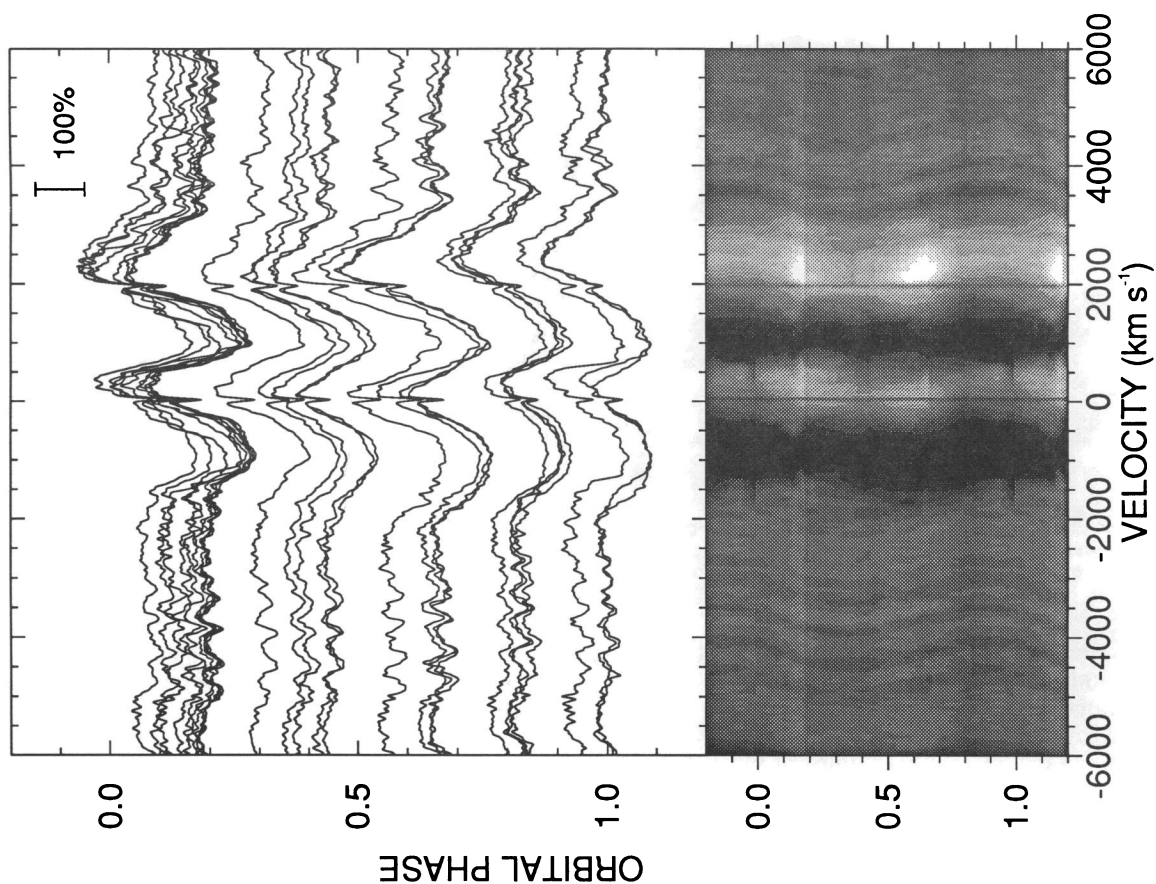


FIG. 4

FIG. 4.—H α profiles plotted in a constant flux representation (i.e., corrected for the varying continuum level) in the same format as Fig. 1

FIG. 5.—IUE spectra of the Si IV $\lambda\lambda$ 1393.755, 1402.770 doublet in the same format as Fig. 1

FIG. 5



The He I $\lambda 6678$ and adjacent He II $\lambda 6683$ absorption lines (Fig. 2) appear to be distorted by relatively weak emission. For example, He II $\lambda 6683$ appears weak near $\phi = 0.1$, where it attains a velocity in the He I $\lambda 6678$ frame close to the velocity of the red peak in the H α emission, and both lines appear weak at other phases and velocities where the H α emission is strong. Thus we suspect that there is a weak component of He I $\lambda 6678$ emission that shares the H α emission properties and systematically distorts the appearance of the absorption lines. The other notable feature in Figure 2 is the development of a very extended blue wing in the He I $\lambda 6678$ profile near orbital phase $\phi = 0.13$ (primary superior conjunction). The overall appearance of the gray-scale image of Figure 2 is very similar to the spectra presented in Struve et al. (1958), which again suggests that the phase-related variations are repeatable over time scales of decades.

3. ULTRAVIOLET STELLAR WIND FEATURES

In this section we describe the orbital-phase variations in velocity and shape of several UV P Cygni lines formed in the stellar wind. We obtained 28 high-dispersion *IUE* spectra of 29 CMa from archival data at the NASA *IUE* Regional Data Analysis Facility in Boulder. The processing of the spectra is described in Paper I, and a journal of the *IUE* spectra is presented in Table 3. The profiles for the wind lines of Si IV $\lambda 1400$, N V $\lambda 1240$, and C IV $\lambda 1550$ are illustrated in Figures 5, 6, and 7, respectively, in the same format as the optical spectra (the profiles for Si IV $\lambda 1400$ and N V $\lambda 1240$ at phases 0.178 and 0.407 were discarded because of problems with the data). The profiles are plotted in the radial velocity system of the blue

member of the doublet. The figures depict the central P Cygni profiles plus numerous weak photospheric and interstellar lines. The shapes of the P Cygni profiles for each ion change significantly with orbital phase. The intensity of the red emission peak of Si IV $\lambda 1400$ attains maxima near the conjunction phases ($\phi = 0.13$ and 0.63). The depth of the blue absorption trough appears to remain approximately constant with phase, but the velocity of the blue edge varies between -1500 km s^{-1} near $\phi = 0.13$ and -2000 km s^{-1} near $\phi = 0.63$. This is very different from the behavior of the UV P Cygni profiles of AO Cas and Plaskett's star (Papers I and II), where we found that the edge velocity *did not* vary with orbital phase. The N V $\lambda 1240$ and C IV $\lambda 1550$ profiles show much the same blue-edge velocity behavior as Si IV $\lambda 1400$.

We measured the radial velocities and intensities, using parabolic fits, of the Si IV $\lambda 1400$, N V $\lambda 1240$, and C IV $\lambda 1550$ P Cygni emission peaks. The radial velocity measures are given in Table 3, and the velocity and intensity data are plotted as a function of orbital phase in Figures 8 and 9. We first tried to fit the velocities using the orbital parameters from Stickland (1989; his all-data solution) with the systemic velocity adjusted to reflect wind outflow. These fits are shown as solid curves in Figure 8 (for $\gamma = 368, 318$, and 312 km s^{-1} for the Si IV, N V, and C IV peaks, respectively), and although these curves provide an approximate match, the observations have a smaller velocity range. Thus we made a second fit using Stickland's orbital parameters but varying the systemic velocity, semiamplitude, and phase of periastron $\phi(0)$, and these fits are given in Table 4 and illustrated as dashed lines in Figure 8. The semiamplitudes are all smaller than the photospheric $K_1 = 224.5 \text{ km s}^{-1}$ (Stickland 1989), a result similar to what we found for AO Cas (Paper I). In addition, the fit to the C IV $\lambda 1550$ peak velocities shows a significant phase lag of 0.07, unlike the case of the other two ions or the corresponding velocity curves derived for AO Cas.

The emission peak intensities of each ion (Fig. 9) show maxima at the conjunction phases. As we described in the last section, an apparent increase in emission strength at conjunctions could result from the varying ratio of constant emission flux to changing continuum flux (with light-curve minima at the conjunctions). If this is the source of the intensity variations, then the rectified intensity at the emission peak should vary as

$$R_\lambda(\phi) = \frac{[R_\lambda(\text{quad}) - 1] + I(\phi)}{I(\phi)}, \quad (2)$$

where $R_\lambda(\text{quad})$ is the average rectified intensity at the quadrature phases. We have plotted this expected variation in intensity as solid lines in Figure 9 using the linearized UV (1330 Å) light curve of Eaton (1978) for $I(\phi)$. The intensities of the N V $\lambda 1240$ and C IV $\lambda 1550$ profiles attain marginally higher maxima than predicted, but the Si IV $\lambda 1400$ emission peak is much stronger than expected at conjunctions.

TABLE 3
UV EMISSION PEAK RADIAL VELOCITIES

ORBITAL PHASE	HJD (2,440,000+)	IMAGE (SWP)	V_r (km s $^{-1}$)		
			Si IV	N V	C IV
0.072.....	4449.124	9620	395	378	410
0.104.....	4119.762	6368	415	394	300
0.134.....	3711.307	2071	315	348	301
0.165.....	3772.949	2715	350	275	305
0.174.....	4150.821	6740	288	250	392
0.178.....	4150.843	6741	...	...	330
0.179.....	3614.842	1369	258	256	329
0.182.....	4454.002	9671	329	215	202
0.184.....	4150.864	6742	245	238	335
0.189.....	4150.886	6743	216	238	280
0.193.....	4150.906	6744	235	226	375
0.295.....	4124.992	6437	262	239	175
0.361.....	3624.432	1417	217	457	99
0.379.....	3624.511	1418	234	346	82
0.407.....	3795.979	2972	...	...	128
0.426.....	3664.259	1716	306	140	195
0.437.....	3778.537	2778	271	164	121
0.573.....	3831.855	3390	228	218	161
0.648.....	4122.150	6400	342	363	216
0.664.....	3964.059	4818	335	299	234
0.666.....	3775.148	2741	350	349	228
0.780.....	4452.238	9654	514	487	410
0.805.....	3960.283	4771	520	441	436
0.812.....	3960.315	4772	526	451	404
0.825.....	3841.748	3485	524	437	436
0.931.....	3719.199	2145	595	481	419
0.986.....	3662.325	1697	532	413	450
0.988.....	3758.989	2515	514	487	430

TABLE 4
ORBITAL SOLUTIONS FROM UV P CYGNI RED PEAKS

Line	γ (km s $^{-1}$)	K_1 (km s $^{-1}$)	$\phi(0)$	σ (km s $^{-1}$)
Si IV $\lambda 1400$	364 ± 8	171 ± 13	0.010 ± 0.025	43
N V $\lambda 1240$	316 ± 5	164 ± 8	0.016 ± 0.014	34
C IV $\lambda 1550$	289 ± 3	167 ± 5	0.071 ± 0.009	51

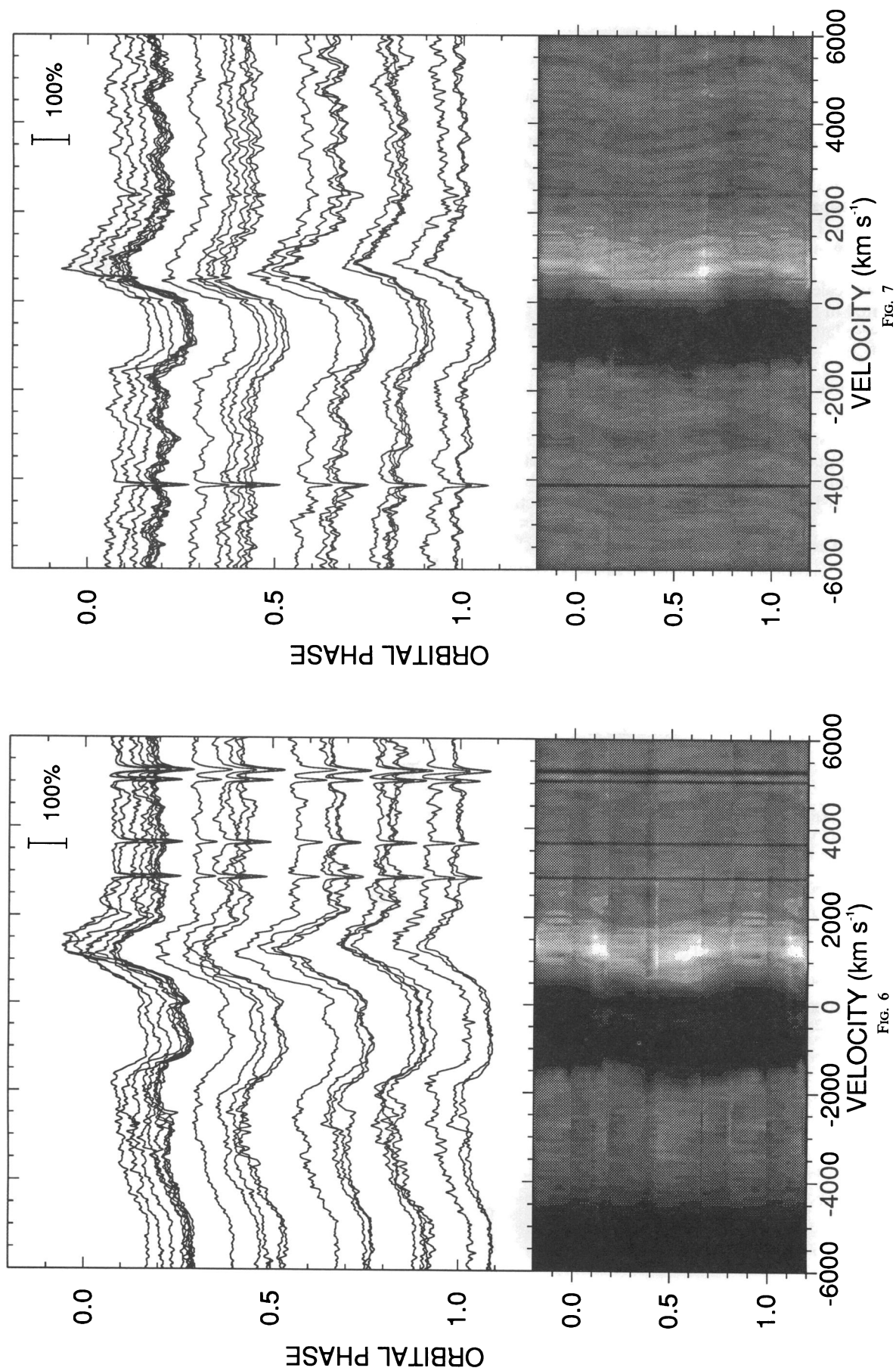


FIG. 6

FIG. 7

FIG. 6.—IUE spectra of the NV $\lambda\lambda 1238.821, 1242.804$ doublet in the same format as Fig. 1

FIG. 7.—IUE spectra of the C IV $\lambda\lambda 1548.185, 1550.774$ doublet in the same format as Fig. 1

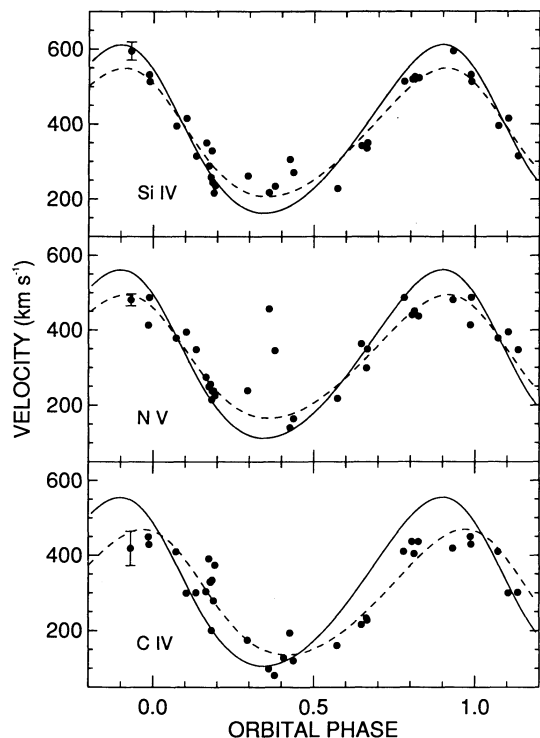


FIG. 8.—Orbital-phase variations of the radial velocity of the red emission peak in the UV P Cygni profiles of the Si IV $\lambda 1400$, N V $\lambda 1240$, and C IV $\lambda 1550$ doublets. Error bars show the average difference between parabolic fits using a narrow and broad range of points in the fit. In each panel the solid line traces the velocity curve of Stickland (1989) shifted in systemic velocity to fit the observations. Dashed lines illustrate the solutions given in Table 4 found by varying γ , K_1 , and $\phi(0)$.

Next, we measured equivalent widths of the blue absorption trough and redmost emission peak for Si IV $\lambda 1400$, and of the entire absorption troughs and emission peaks for N V $\lambda 1240$ and C IV $\lambda 1550$, in the same way as we did for Plaskett's star (Paper II). The measurements for the absorption were made from -2500 to about -500 km s $^{-1}$ for Si IV $\lambda 1400$, from -2200 to about 500 km s $^{-1}$ for N V $\lambda 1240$, and from -2200 to about 0 km s $^{-1}$ for C IV $\lambda 1550$. The emission measurements were all made from the upper boundaries listed above (except for Si IV $\lambda 1400$, where we started from about 1500 km s $^{-1}$) out to 3100 , 1750 , and 1500 km s $^{-1}$ for Si IV $\lambda 1400$, N V $\lambda 1240$, and C IV $\lambda 1550$, respectively. The actual boundaries between the absorption and emission parts of the profile were defined individually for each spectrum as the first point redward of the absorption trough with an intensity greater than unity. The results are listed in Table 5 and plotted against orbital phase in Figure 10. We find that the emission (*open circles*) is strongest at conjunctions, which, again, could be the result of the varying continuum level. Because of changes in continuum flux, the emission equivalent width will appear to vary as

$$W_\lambda(\phi) = \frac{W_\lambda(\text{quad})}{I(\phi)}, \quad (3)$$

where $W_\lambda(\text{quad})$ is the average equivalent width at quadrature phases. We constructed curves of equivalent-width variability (shown as dashed lines in Fig. 10) using again the UV light curve of Eaton (1978). The observed emission equivalent widths do vary in accord with our expectations for constant emission flux in the cases of N V $\lambda 1240$ and C IV $\lambda 1550$, but the

increase in the Si IV $\lambda 1400$ emission strength at conjunctions is much more dramatic than expected. The absorption equivalent widths (*filled circles*) are less variable but display local minima near primary superior conjunction ($\phi = 0.13$).

Finally, we measured the velocities of the blue absorption edge of the P Cygni profiles (v_{edge}). This was done on a computer terminal screen using an interactive cursor to measure the position where the blue edge of the profile meets the continuum. In the case of the most saturated line, C IV $\lambda 1550$, we also measured the velocity of the shortward edge of the zero-intensity core, v_{black} , which Prinja, Barlow, & Howarth (1990) argue is a better estimate of the wind terminal velocity. These measurements are listed in Table 6, and the v_{edge} values are plotted against orbital phase in Figure 11 along with the radial velocity curve of the primary (which has been shifted in systemic velocity to the average of v_{edge} in each case). These diagrams show considerable scatter, which is partially due to the fact that the blue edge is not always well defined, but which is also due to real variations that are unrelated to orbital phase (see, for example, the large range in v_{edge} for the bottom three profiles in Fig. 5). Nevertheless, there is an apparent trend toward velocity extrema at the conjunctions, i.e., less negative values near $\phi = 0.13$ and more negative values near $\phi = 0.63$, with a velocity range $\sim 2K_1$. The v_{black} velocities, on the other hand, show little evidence of any phase-dependent variability (with the exception of the spectra obtained at phases 0.134, 0.573, and 0.648). We will return to these properties in the

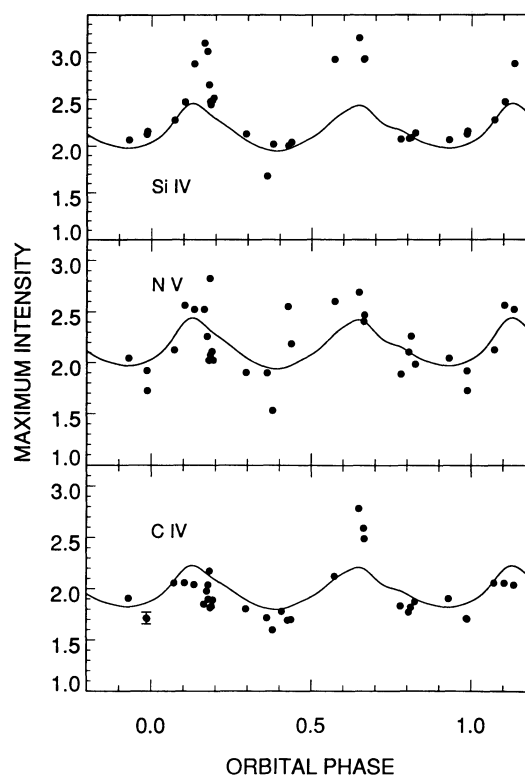


FIG. 9.—Orbital-phase variations of the maximum emission intensity of the red peak in the UV P Cygni profiles of the Si IV $\lambda 1400$, N V $\lambda 1240$, and C IV $\lambda 1550$ doublets. The solid curve traces the expected intensity variations for a constant emission component and a varying continuum, based on the UV light curve of Eaton (1978). Error bars show the average difference between parabolic fits using a narrow and broad range of points in the fit.

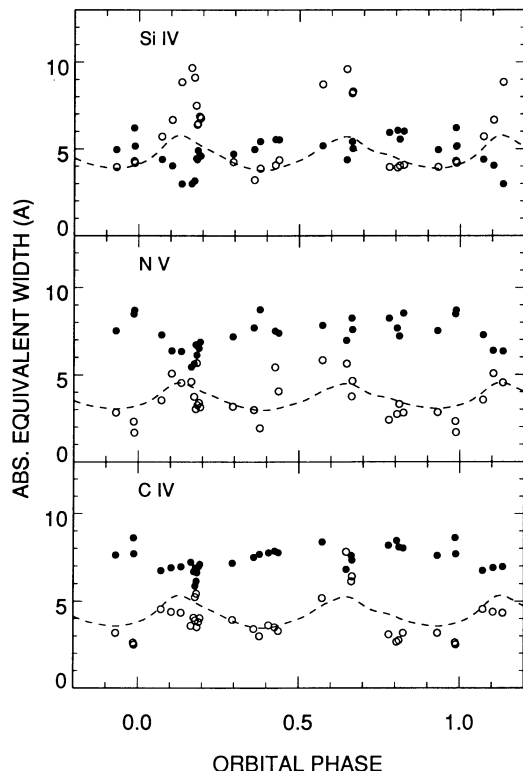


FIG. 10.—Orbital-phase variations of the absolute equivalent width of the absorption (*filled circles*) and emission (*open circles*) components of the UV P Cygni profiles of the Si IV $\lambda 1400$, N V $\lambda 1240$, and C IV $\lambda 1550$ doublets. The dashed curve represents the variations expected in the emission equivalent width assuming a constant component of emission and a varying continuum, based on the UV light curve of Eaton (1978). The errors in the equivalent widths are less than the symbol size.

following section, where we develop a simple model to help explain the orbital variations of the optical and UV spectral lines.

4. DISCUSSION

Our goal in this section is to develop a qualitative picture of the wind interaction that is consistent with the phase-related variations described in the last two sections. We begin with the physical parameters for the two stars, and then we develop a model for the wind collision based on the H α emission properties. Finally, we discuss the UV P Cygni profiles and demonstrate that their orbital variations are not inconsistent with the H α bow shock model. A brief summary concludes this section.

As a starting point, we present in Figure 12 a schematic drawing of the binary as viewed from above the orbital plane. The dimension of the stars are taken from one solution to the V-band photometric light curve of van Genderen et al. (1988), which we will discuss in a separate paper (Baguolo et al. 1992b). The light-curve fit is similar to those presented by Leung & Schneider (1978), with the important exception that our geometrical shapes are calculated including radiation pressure. Leung & Schneider found that the best fits are obtained by assuming an overcontact configuration, but we prefer a semidetached model with a smaller secondary (which provides smaller ratios of secondary to primary flux and line depth that are more consistent with the observations). Briefly, the model assumes the following: a mass ratio $q = M_2/M_1 = 1.0$ intermediate among published values (Hutchings 1977; Leung & Schneider 1978); spectral classifications of O8 I and B0 I for

TABLE 5
UV P CYGNI EQUIVALENT WIDTHS

ORBITAL PHASE	ABSORPTION W_λ (Å)			EMISSION W_λ (Å)		
	Si IV	N v	C IV	Si IV	N v	C IV
0.072.....	4.39	7.29	6.75	-5.71	-3.55	-4.55
0.104.....	4.04	6.38	6.91	-6.66	-5.08	-4.40
0.134.....	2.98	6.34	6.96	-8.85	-4.55	-4.35
0.165.....	3.00	5.45	7.22	-9.67	-4.61	-3.60
0.174.....	3.17	5.64	6.69	-9.11	-3.75	-4.07
0.178.....	...	...	5.88	...	...	-5.25
0.179.....	4.45	6.72	6.90	-7.50	-3.04	-3.92
0.182.....	4.39	6.13	6.15	-6.39	-5.67	-5.44
0.184.....	4.91	6.64	6.64	-6.45	-3.27	-3.53
0.189.....	4.65	6.52	6.97	-6.86	-3.40	-3.82
0.193.....	4.60	6.88	7.10	-6.77	-3.14	-4.05
0.295.....	4.71	7.17	7.17	-4.25	-3.17	-3.94
0.361.....	4.98	7.70	7.50	-3.22	-2.98	-3.42
0.379.....	5.43	8.74	7.68	-3.88	-1.94	-3.01
0.407.....	...	...	7.76	...	...	-3.64
0.426.....	5.54	7.51	7.86	-4.07	-5.42	-3.52
0.437.....	5.53	7.39	7.77	-4.36	-4.05	-3.31
0.573.....	5.19	7.83	8.38	-8.72	-5.83	-5.20
0.648.....	4.38	6.96	6.82	-9.59	-5.63	-7.82
0.664.....	5.41	8.24	7.60	-8.20	-3.75	-6.15
0.666.....	5.03	7.57	7.35	-8.30	-4.64	-6.43
0.780.....	5.94	8.24	8.19	-3.96	-2.39	-3.10
0.805.....	6.06	7.67	8.46	-3.93	-2.73	-2.67
0.812.....	5.55	7.20	8.09	-4.04	-3.31	-2.76
0.825.....	6.01	8.53	8.03	-4.08	-2.82	-3.19
0.931.....	4.96	7.52	7.61	-3.96	-2.84	-3.19
0.986.....	6.20	8.48	8.61	-4.30	-2.32	-2.64
0.988.....	5.16	8.70	7.69	-4.20	-1.69	-2.51

TABLE 6
UV P CYGNI ABSORPTION VELOCITIES

ORBITAL PHASE	v_{edge} (km s $^{-1}$)			v_{black} (km s $^{-1}$)
	Si IV	N v	C IV	C IV
0.072.....	-1566	-1601	-1566	-1068
0.104.....	-1566	-1779	-1566	-1089
0.134.....	-1566	-1637	-1530	-1324
0.165.....	-1673	-1388	-1424	-1004
0.174.....	-1459	-1495	-1601	-961
0.178.....	-1673	-1459	-1530	-1153
0.179.....	-1459	-1495	-1495	-961
0.182.....	-2029	-1530	-1566	-961
0.184.....	-1494	-1566	-1566	-961
0.189.....	-1530	-1424	-1352	-982
0.193.....	-1566	-1495	-1352	-961
0.295.....	-1851	-1993	-1566	-1110
0.361.....	-1779	-2100	-1851	-1068
0.379.....	-1957	-2064	-1886	-1110
0.407.....	-1922	-2029	-1957	-1025
0.426.....	-1886	-2135	-1779	-1110
0.437.....	-1957	-1993	-1886	-1068
0.573.....	-2135	-2135	-1957	-1473
0.648.....	-2064	-1744	-1637	-1388
0.664.....	-1922	-2100	-1673	-1004
0.666.....	-2064	-2029	-1744	-1025
0.780.....	-1922	-1851	-1637	-1089
0.805.....	-1708	-1815	-1601	-982
0.812.....	-1673	-1744	-1566	-982
0.825.....	-1851	-1799	-1708	-1089
0.931.....	-1601	-1566	-1424	-854
0.986.....	-1957	-1851	-1708	-961
0.988.....	-1779	-1779	-1566	-1089

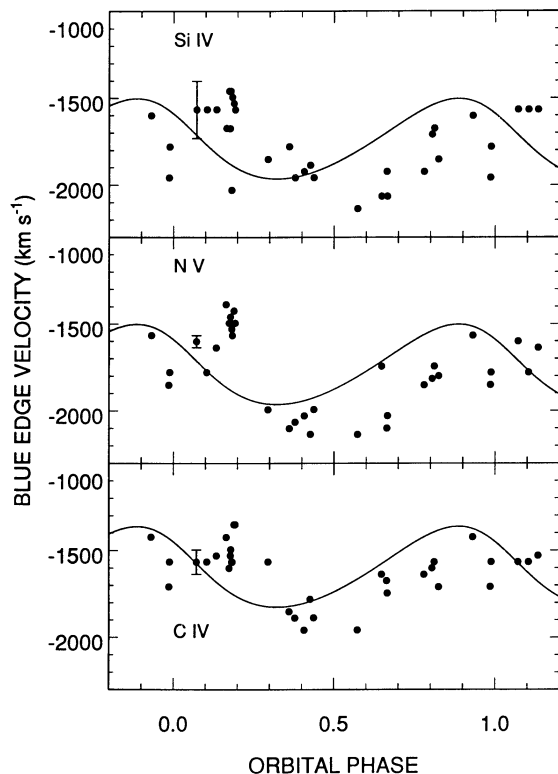


FIG. 11.—Orbital-phase variations of the blue-edge velocity of the UV P Cygni profiles of Si IV $\lambda 1400$, N V $\lambda 1240$, and C IV $\lambda 1550$. In each panel the solid curve traces the velocity curve of the primary star shifted in velocity to match the average blue-edge velocity. Error bars show the average difference between two independent velocity measurements.

the primary and secondary (with effective temperatures of 33,000 and 26,000 K); a Roche-filling primary; and a secondary radius of $\approx 80\%$ of its Roche radius. The best-fit inclination is then $i = 74^\circ$ (slightly larger than the values obtained by Leung & Schneider), which yields masses $M_p = M_s = 25 M_\odot$ and radii $R_p = 30 R_\odot$ and $R_s = 25 R_\odot$. The light-curve solutions admit a range of $\Delta R_s = \pm 5 R_\odot$, and thus the greatest uncertainty in the drawing is the size of the secondary.

We next turn to the origin of the H α emission. This emission is the result of recombination, and the emission flux will depend on the square of the gas density, so we expect that the emission has its source in relatively high-density regions near the stars or near a bow shock formed by the winds. Furthermore, because of the overwhelming evidence for stellar wind mass loss in this system (see below), it is hard to imagine that the emitting gas is stationary in the frame of reference of the binary system. Instead, we suggest that we are observing gas moving through high-density regions, and we rule out models involving stationary circumbinary clouds or disks.

We described in § 2 how the H α feature appears to be the sum of a broad emission plateau plus a P Cygni component. The velocity curve of the P Cygni component is very similar to that of the primary, and this component almost certainly forms in the base of the wind of the primary star. The difference in systemic velocity between the velocity curves of the P Cygni absorption core and the photospheric lines is $\approx -200 \text{ km s}^{-1}$, and we have used the velocity curves of Friend & Castor (1982) to find the approximate radii at which the wind would attain this outflow velocity. The volume in the primary's wind with

outflow velocities smaller than 200 km s^{-1} is indicated by the shaded area in Figure 12 that surrounds the primary (Roche-distorted) star. We found that the velocity curve of the P Cygni absorption component has a smaller range in velocity than the photospheric lines, and that the absorption core disappears near $\phi = 0.6$ when the hemisphere of the primary facing the secondary is directed away from us. Although both these features could be the result of residual emission filling in the absorption core at selected phases, these characteristics could also be due to enhancement of the wind outflow in the direction of the secondary. Friend & Castor (1982) have shown that the wind can become significantly focused in the direction of the companion when the primary approaches the size of the Roche lobe. Thus the center of light of the P Cygni component would be shifted toward the secondary, yielding a smaller velocity semi-amplitude, and the greatest outflow near the L1 point would be most occulted near primary inferior conjunction ($\phi = 0.63$). A focused wind could also explain the observed blueward extension of the He I $\lambda 6678$ line near primary superior conjunction (Fig. 2) as the result of the enhanced outflow at the base of the wind near the inner Lagrangian point.

We next examine the characteristics of the broad H α emission component. The emitting region must satisfy several conditions based on the observed line behavior: (1) The gas distribution must be approximately centered on the system center of mass, since there is no evidence of orbital velocity variations in the broad component. Any other placement in the system would require a gas-flow vector that would exactly negate the orbital velocity vector. (2) The dimension of the cloud must be greater than the stellar diameters because there are no significant decreases in emission strength at the conjunctions when occultation effects should be important. (3) The velocities in the extreme H α wings are comparable to the wind terminal velocity v_∞ (see below), so at least part of the emission

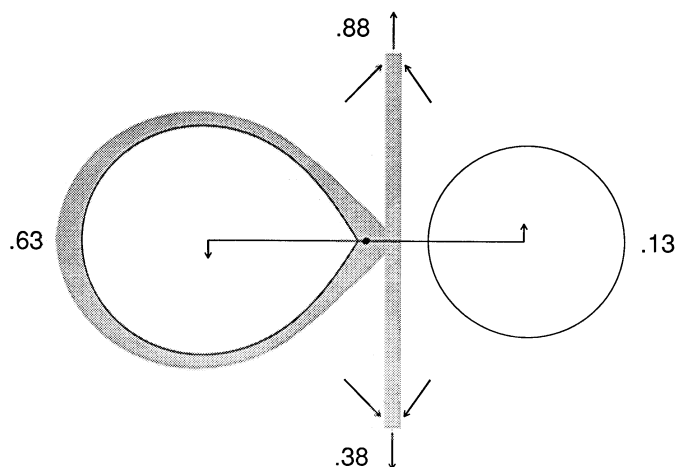


FIG. 12.—Cartoon view of the system geometry as seen from above the orbital plane. The filled circle on the axis between the stars marks the center of mass. The small vectors at the center of each star, perpendicular to the axis, represent the respective orbital velocities. The shaded regions represent the H α -emitting regions: the P Cygni component forms close to the primary, while the broad emission component forms in a bow shock between the stars. The large vectors at the outer visible annulus of the bow shock represent the flow of the two winds into the shock and the flow outward within the shock. Orbital phases are marked on the periphery of the diagram in the direction of the observer.

must come from regions far enough from the primary to have attained a large outflow velocity. (4) The broad component has a nearly constant width, so we must observe the same range in outflow velocities throughout the orbit.

We believe that the simplest model that can satisfy these requirements places the source of the broad component in a dense region (mainly optically thin) where the winds collide along a plane perpendicular to the axis joining the stars and close to the center of mass. The central disk of this plane is shown as a shaded region in the center of Figure 12. In this figure the outer annulus of the disk has a distance from the center of the primary, r , of approximately $1.5 R_p$, where R_p is the volume-averaged radius of the primary. If the wind follows a standard velocity law

$$v(r) = v_\infty \left(1 - \frac{R_p}{r}\right)^{0.8} \quad (4)$$

(Friend & Abbott 1986), then at this distance the wind would reach an outflow velocity of approximately 640 km s^{-1} (for $v_\infty = 1066 \text{ km s}^{-1}$; see below), which is close to the observed value in the H α wings. We suggest that the observed velocities in the broad emission component correspond to the wind velocities of the winds of both stars as they enter the shock region plus the outflow velocity of gas within the shock itself. Thus we would expect to observe a range in velocity from small values, for the slow-moving gas close to the axis, to large values associated with accelerated gas near the outer annulus, where densities are still high enough to produce a significant emission flux. The large velocity components found in the outer annulus are illustrated as arrows in Figure 12. These vectors represent the gas entering the shock from the two winds and the outflow within the shock directed away from the axis joining the stars. Luo et al. (1990) show that in this simple geometry the outflow component within the shock will have a velocity equal to the vector component of the wind inflow perpendicular to the axis joining the stars.

The merit of this simple model is that it satisfies the requirements listed above: (1) Since we observe inflow from the winds of both stars, and since the bow shock is located close to the center of mass, the integrated vector sum of velocities from gas in the shock will be approximately zero, and thus there will be no orbital velocity variations. (2) The emitting region is large enough that occultation effects will not be too severe. Even at conjunction phases, the outer portion of the shock region will be readily visible. The brightening at $\phi = 0.13$ near $V_r = 300 \text{ km s}^{-1}$ may result from the superposition of redward emission from the P Cygni component of the primary with emission from the wind of the secondary flowing into the shock. Another emission maximum half a cycle later does not occur, presumably because the larger disk of the primary is more effective in blocking the central part of the shock zone. (3) Densities are high enough in the outer parts of the shock to produce H α emission with velocities reflecting the acceleration of the radiatively driven wind. (4) The overall range in observed velocities will change little with orbital phase, since the gas is mainly optically thin and we see contributions from all through the shock zone that reflect gas motion both approaching and receding from us. For example, emission from the outer annulus will display more or less the same velocity extrema at orbital phase $\phi = 0.13$ as at $\phi = 0.38$ (see Fig. 12). The simple model predicts that highest velocities will be observed at $\phi = 0.26$ (one-eighth of an orbit past superior

conjunction of the primary) and each succeeding quarter of the orbit, but these same phases correspond to orientations where sections of the annulus with extreme velocity are occulted by and/or projected onto the stellar disks, and consequently we expect the actual observed velocity range to be uniform.

The chief deficiency of the model is that the presumed geometry of a planar shock between the stars is applicable only to systems with equally strong winds. Instead, since we have assumed a more luminous primary, we would expect the primary to have the dominant stellar wind which would form a bow shock wrapped around the secondary. For example, given the temperatures and radii listed at the beginning of this section, the ratio of mass-loss rates should be $\dot{M}_s/\dot{M}_p = 0.1$ (Howarth & Prinja 1989). The asymptotic shape of the bow shock surface depends on the momentum ratio

$$\lambda = \frac{\dot{M}_s v_{\infty,s}}{\dot{M}_p v_{\infty,p}} \quad (5)$$

(Luo et al. 1990), and for equal terminal velocities, $v_{\infty,s}/v_{\infty,p} = 1$, the momentum ratio leads to a bow shock that should wrap around the secondary with an opening half-angle of $\theta \approx 50^\circ$ from the axis joining the stars (Girard & Willson 1987). However, if the H α emission formed along a bow shock wrapped around the secondary, then we would expect to observe some net flow in the direction of the secondary (i.e., blueshifted at $\phi = 0.13$), contrary to the actual observations. Similar arguments rule out a model in which the emission forms entirely in the focused wind of the primary. Our simple model for H α might be taken as evidence for an unusually strong secondary wind, but we caution that the shape of the bow shock could be influenced by differences in wind velocity. For example, the velocity of the primary's wind near the shock region between the stars may be low because of the restricted distance available for acceleration and because the focused portion has a lower than normal acceleration (Friend & Castor 1982). The secondary's wind, on the other hand, may have more space to accelerate and might attain a higher velocity when it reaches the shock. If the ratio of secondary to primary wind velocity at the shock is sufficiently large, then a more planar bow shock may result.

Next we turn our attention to the large-scale wind structure that is reflected in the shapes of the UV P Cygni line profiles which are formed by scattering of photons by wind material. Our velocity measurements of the red emission peaks of the dominant P Cygni lines Si iv $\lambda 1400$, N v $\lambda 1240$, and C iv $\lambda 1550$ follow the velocity curve of the primary star (Fig. 8), and thus we can confirm the result from prior UV studies of 29 CMA (McCluskey & Kondo 1976; Drechsel et al. 1981; Corcoran & Heap 1989) that the P Cygni lines are formed predominantly in the wind of the primary star. There are two subtle differences between the UV P Cygni and the photospheric velocity curves. First, the amplitude of the P Cygni velocity curves (Table 4) is small compared with the photospheric curve. We found a similar reduced amplitude in the UV P Cygni velocity curves of AO Cas (Paper I). There are two possible reasons for this difference: (1) the focused wind of the primary produces a shift toward the secondary in the net distribution of scattering ions, which results in a smaller semiamplitude of orbital motion, and/or (2) the P Cygni profile of the secondary is blended together with that of the primary, and line blending biases the measurements to smaller velocities. The other peculiarity in the UV velocity curves is the apparent phase lag of C iv $\lambda 1550$

(Table 4). Drechsel et al. (1981) found a similar phase lag in velocity curves they constructed for the line C III $\lambda 1175$. They suggest that the phase lag is due in part to a retardation effect in which the velocities of the P Cygni lines reflect the orbital motion of the primary at an earlier time when the scattering ions left the photosphere. If this explanation is correct, then presumably it is the differences in the optical depths of the P Cygni lines that renders the phase lag visible only in C IV $\lambda 1550$ (more optically thick than the other two lines), but radiative transfer calculations are needed to verify this suggestion.

We also found that the P Cygni peaks attained local maxima near the conjunction phases that are especially striking in the case of Si IV $\lambda 1400$ (Fig. 9). Corcoran & Heap (1989) first noticed this phase variation, which they attributed to a lack of scattering ions in the zone occulted by the disk of the secondary. This occulted region presents its largest projected area on the sky at the quadrature phases, and thus a significant number of scattering ions will be absent relative to the case of an undisturbed wind, and there will be a corresponding reduction in the red emission peak in the P Cygni profile. At superior conjunction of the primary, the occultation zone will be directed toward us, and it will have little or no influence on the reduction of the redward emission peak. Recently Stevens (1993) has shown that brightenings of the red peaks can occur at conjunctions even in the case of stars with equal-strength winds. Stevens has used Monte Carlo simulations of photons escaping from a colliding winds binary to study the orbital-phase dependence of the line shapes. He presents model profiles for the ideal case of stars of equal wind strengths, but differing luminosity, viewed in the orbital plane $i = 90^\circ$ (see his models 1a and 1b). In these models it is the wind of the secondary (rather than just its occulting disk) that blocks the wind of the primary and creates a large zone surrounding the secondary where photons of the primary may or may not be scattered by the secondary's wind. These models demonstrate that the red peak attains maxima at the conjunctions just as observed. However, for inclinations $i < 90^\circ$, we would expect that the maximum at inferior conjunction of the more luminous star would tend to decrease in strength because the zone surrounding the secondary would no longer be fully occulted by the primary. The inclination is $i \approx 74^\circ$ for 29 CMa, and thus the maxima might be expected to differ in strength. We suggest that the near-equality in the Si IV maxima at the two conjunctions may reflect a density enhancement between the stars which would provide an increase in the number of redshifted scattering ions at primary inferior conjunction. Presumably the conjunction brightenings are observed in the Si IV doublet only because this transition has a lower optical depth than the others and thus better samples conditions closer to the stars.

Finally we turn to the variations in the velocity of the blue edge of the UV P Cygni lines, v_{edge} , that superficially resemble the velocity curve of the primary but appear to lag by approximately 0.25 in orbital phase (Fig. 11). Prinja et al. (1990) noted the v_{edge} change in the P Cygni lines of 29 CMa and suggested that, because of eclipses in the system, the profiles observed at $\phi = 0.13$ actually correspond to the wind of the secondary star. This cannot be entirely correct, because the eclipses are partial (the flux ratio at $1557 \text{ \AA}$ is $F_s/F_p = 0.56$ at primary eclipse according to the light-curve model cited at the outset of this section) and because v_{edge} varies continuously with orbital phase (not just during the eclipse phases). Here we explore two approaches to the problem of the v_{edge} variations based on two very different assumptions about the location of the wind material with the highest velocity.

The simplest assumption is that the blue edge is formed by high-velocity scattering ions very distant from the source star (see eq. [4]). The v_{edge} variations could then be explained in several ways, all of which are somewhat problematical: (1) Corcoran & Heap (1989) propose that the variations are due to orbital motion with a phase lag due to the retardation effect described above. If so, these edge variations should be common to all O-type spectroscopic binaries, but in fact the blue edges appear constant in each of the other three systems we have examined (AO Cas, Plaskett's star, and ι Ori). (2) The focused wind of the primary probably has a slower and denser wind in the direction of the secondary, so the absolute value of the blue edge velocity could decline near $\phi = 0.13$ when this part of the wind is directed toward us. However, as Corcoran & Heap have argued, the highest outflow velocities should then be found at the quadratures, not at primary inferior conjunction as observed. (3) The geometrical obscuration of the primary's wind by the disk of the secondary could remove the highest velocity scattering ions in the shadow region beyond the secondary and cause a reduction in the absolute value of v_{edge} observed near $\phi = 0.13$ (Drechsel et al. 1981). This model predicts that the variations will be limited to orbital phases near primary eclipse, whereas we find that v_{edge} varies in a more or less continuous fashion throughout the orbit. (4) A bow shock formed by colliding winds could block the wind of the primary from entering a large region surrounding the secondary and, as in model 3 above, could cause a blue-edge reduction near $\phi = 0.13$. Stevens (1993) has performed radiative transfer calculations that demonstrate this effect in the ideal case where the stars have equal-strength winds but the primary is much more luminous and only its wind is optically thick (see his model 1b). These model profiles do indeed show a reduction in the blue edge during phases when the line of sight to the primary crosses the bow shock (between quadrature phases in the equal-winds case). However, we find that v_{edge} varies continuously through the orbit, which in the context of this model would indicate that the bow shock wraps around the primary, an untenable assumption. Furthermore, at $\phi = 0.13$, v_{edge} attains an absolute value of approximately 1500 km s^{-1} , which is a much larger value than could be attained by radiative acceleration in the space between the stars. Thus we conclude that none of these models are entirely satisfactory.

Instead of placing the fastest wind material at great distance from the source, an alternative possibility is that the high-velocity gas occurs in shocks in the wind relatively close to the star. Howarth & Prinja (1989) and Prinja et al. (1990) have shown that there is an important distinction between the blue-edge velocity v_{edge} (corresponding to the position where the profile intersects the continuum) and the shortward edge of the black absorption core v_{black} in saturated lines. Prinja et al. argue that the more reliable estimate of the wind terminal velocity v_∞ is given by $-v_{\text{black}}$ and that the greater $-v_{\text{edge}}$ velocity reflects turbulence in the wind perhaps due to the formation of large-scale shocks associated with instabilities in the radiatively driven wind (Owocki, Castor, & Rybicki 1988). This model for high-velocity gas is supported by two lines of evidence. First, Prinja (1991) has demonstrated a connection between the onset of new episodes of discrete absorption components (presumed to be formed in large-scale shocks) and increases in the absolute value of v_{edge} in the UV P Cygni profiles of the O stars 68 Cyg and ξ Per (and also possibly ζ Pup; see Prinja et al. 1992). Second, Henrichs (1991) has found correlated variations between v_{edge} and the equivalent width of the emission line He II $\lambda 4686$ (formed in the dense base

of the wind near the star) in the spectrum of λ Cep. Taken together, these observations suggest that the blue-edge variations are the result of time-variable shocks in the wind that occur relatively close to the star. Since the occurrence of shocks is a stochastic process, this model could help explain the large scatter we find superposed upon the orbital variations in v_{edge} (see Fig. 11).

We speculate that there are at least two ways in which shocks could act to create the orbital variations in v_{edge} . First, the formation of large-scale shocks may be inhibited in the hemisphere of the primary's wind directed toward the secondary because of the limited space available between the stellar surface and the bow shock and, perhaps, because of the denser, slower wind flow in the focused part of the wind. Thus we would expect $-v_{\text{edge}}$ to be smaller when this hemisphere is directed toward us (at $\phi = 0.13$). The second possibility is that, since the shocks form relatively close to the primary, their apparent Doppler shift may include an orbital component of velocity. It remains to be seen whether a retardation effect (see above) could explain the phase lag of 0.25 that we find between the velocity curves of v_{edge} and the photospheric lines.

If the turbulence model for v_{edge} is correct, then we should look instead to v_{black} to evaluate changes in the wind at distance from the primary. The saturated line C IV $\lambda 1550$ provides the best feature to study v_{black} in the spectrum of 29 CMa (see Fig. 7). We find $-v_{\text{black}} \approx 1066 \text{ km s}^{-1}$ (Table 6), and this velocity is approximately constant throughout the orbit. Thus we suggest that the observed wind terminal velocity is also constant, just as we have found in other binary systems. We suspect that this constancy is due to the fact that at great distance from the primary our line of sight includes wind contributions from all orbital phases, so that the orbital motion is effectively averaged to zero.

We described above how a bow shock could remove the high-velocity portion of the primary's wind directed toward the secondary and lead to orbital changes in v_{edge} or, more plausibly, in v_{black} . The constancy of v_{black} might be taken to indicate that our line of sight to the primary never crosses the bow shock, and that therefore any bow shock must wrap very tightly around the secondary to avoid an occultation of the primary from our line of sight (i.e., with a cone opening half-angle relative to the axis joining the stars of $\theta < 90^\circ - i \approx 16^\circ$). However, we caution that if the secondary has an optically thick wind with a similar terminal velocity, the phase variations in the blue edge of the absorption core may vanish. For example, Stevens (1993) has calculated model P Cygni profiles for the case of colliding winds of equal momentum and large optical depth and stars of equal luminosity (his model 2a). These profiles have a constant blue edge owing to the fact that blueshifted photons can be scattered by the wind of either the primary or the secondary. None of Steven's ideal cases can be directly applied to 29 CMa, but his results indicate that a wide bow shock can exist even in cases where no obvious blue-edge variations are observed.

Our assumption that $-v_{\text{black}} = v_\infty$ is consistent with the physical parameters we have adopted for the primary. Corcoran & Heap (1989) have shown how the ratio v_∞/v_{esc} can be used to test the assumed mass and radius of the primary, since the escape velocity depends on both. Prinja et al. (1990) find that this ratio is 1.98 for the Ofp stars in their sample, and from $v_\infty = -v_{\text{black}} = 1066 \text{ km s}^{-1}$, we estimate an escape velocity of $v_{\text{esc}} = 538 \text{ km s}^{-1}$. This compares well with the escape velocity derived from the model parameters used in Figure 12: $v_{\text{sec}} = [2GM(1 - \Gamma)/R]^{1/2} = 483 \text{ km s}^{-1}$, for $M_p = 25 M_\odot$, $R_p = 32 R_\odot$, and $\Gamma_p = 0.26$ (the ratio of radiative to gravitational acceleration). Furthermore, the relative sizes of v_{edge} and v_∞ we derive are similar to those found in single stars: the average value of v_∞/v_{edge} from all our spectra is 0.66, which is close to the value of 0.70 found by Prinja et al. (1990) in five single Ofp stars.

In conclusion, our analysis suggests that the broad, stationary component of the H α emission probably originates in a bow shock along a plane midway between the stars where the winds collide. This is a surprising result for two reasons. First, there are good reasons to suspect that the primary has the dominant stellar wind in the binary (e.g., the similarity of the velocity curves of the H α and UV P Cygni features to the primary's velocity curve, and the predicted ratio of mass-loss rates from the luminosity ratio), and consequently we would expect the bow shock to wrap around the secondary. However, the shape of the bow shock is defined by the momentum balance of the winds, and if the primary's wind is indeed focused, then it will be slower than normal as it enters the shock, and thus a wider bow shock opening may result. The second reason why a wide bow shock is surprising is that we observe no large-scale orbital variations in the shortward edge of the black core in the C IV $\lambda 1550$ P Cygni line which might result from the bow shock blocking the high-velocity part of the primary's wind directed toward the secondary. If, however, the secondary has an optically thick wind (which seems probable for a B0 I star), then the secondary's wind may provide the scattering ions to maintain absorption at the shortward edge of the P Cygni core. Clearly, radiative transfer calculations are needed for the wind geometry we have outlined here to determine whether the H α and UV P Cygni line variations can be reconciled in a colliding-winds model.

We thank W. G. Baguolo, Jr., A. W. Fullerton, and an anonymous referee for helpful comments. D. R. G. gratefully acknowledges the financial support of a McDonald Observatory Postdoctoral Fellowship and a Natural Sciences and Engineering Research Council of Canada Postdoctoral Fellowship at the time of the observations. D. R. G. also expresses his thanks to the American Astronomical Society for a Chrétien International Research Grant that provided partial funding for the purchase of a workstation used in this analysis. This research was supported by the NASA Astrophysics Data Program grant NAG 5-1218.

REFERENCES

- Baguolo, W. G., Jr., & Gies, D. R. 1991, *ApJ*, 376, 266
 Baguolo, W. G., Jr., Gies, D. R., Hahula, M. E., & Wiemker, R. 1992a, in preparation
 Baguolo, W. G., Jr., Gies, D. R., & Wiggs, M. S. 1992b, *ApJ*, 385, 708
 Brault, J. W., & White, O. R. 1971, *A&A*, 13, 169
 Chlebowski, T., & Garmany, C. D. 1991, *ApJ*, 368, 241
 Conti, P. S. 1974, *ApJ*, 187, 539
 Conti, P. S., & Leep, E. M. 1974, *ApJ*, 193, 111
 Corcoran, M. F., & Heap, S. R. 1989, preprint
 Drechsel, H., Rahe, J., Kondo, Y., & McCluskey, G. E. 1981, *A&A*, 94, 285
 Drew, J. E. 1990, *ApJ*, 357, 573
 Eaton, J. A. 1978, *ApJ*, 220, 582
 Ebbets, D. 1982, *ApJS*, 48, 399
 Friend, D. B., & Abbott, D. C. 1986, *ApJ*, 311, 701
 Friend, D. B., & Castor, J. I. 1982, *ApJ*, 261, 293
 Fullerton, A. W. 1989, *PASP*, 101, 118

- Gies, D. R., & Wiggs, M. S. 1991, *ApJ*, 375, 321 (Paper I)
Girard, T., & Willson, L. A. 1987, *A&A*, 183, 247
Heap, S. R. 1982, in *Advances in Ultraviolet Astronomy: Four Years of IUE Research*, ed. R. D. Chapman (NASA CP-2238), 562
Henrichs, H. 1991, in *Rapid Variability of OB-Stars: Nature and Diagnostic Value*, ed. D. Baade (ESO CWP No. 36; Garching: ESO), 199
Howarth, I. D., & Prinja, R. K. 1989, *ApJS*, 69, 527
Hutchings, J. B. 1977, *PASP*, 89, 688
Kallrath, J. 1991, *MNRAS*, 248, 653
Leung, K.-C., & Schneider, D. P. 1978, *ApJ*, 222, 924
Lucy, L. B., & Sweeney, M. A. 1971, *AJ*, 76, 544
Luo, D., McCray, R., & Mac Low, M.-M. 1990, *ApJ*, 362, 267
McCluskey, G. E., & Kondo, Y. 1976, *ApJ*, 208, 760
Morbey, C. L., & Brosterhus, E. B. 1974, *PASP*, 86, 455
Ninkov, Z., Walker, G. A. H., & Yang, S. 1987a, *ApJ*, 321, 425
Ninkov, Z., Yang, S., Hill, G. M., & Walker, G. A. H. 1987b, *PASP*, 99, 284
Ogata, H., & Hukusaku, C. 1977, *Inf. Bull. Var. Stars*, No. 1235
Owocki, S., Castor, J. I., & Rybicki, G. B. 1988, *ApJ*, 335, 914
Prinja, R. K. 1991, in *Rapid Variability of OB-Stars: Nature and Diagnostic Value*, ed. D. Baade (ESO CWP No. 36; Garching: ESO), 211
Prinja, R. K., et al. 1992, *ApJ*, 390, 266
Prinja, R. K., Barlow, M. J., & Howarth, I. D. 1990, *ApJ*, 361, 607
Shore, S. N., & Brown, D. N. 1988, *ApJ*, 334, 1021
Stevens, I. R. 1993, *ApJ*, 404, 281
Stevens, I. R., Blondin, J. M., & Pollock, A. M. T. 1992, *ApJ*, 386, 265
Stickland, D. J. 1989, *Observatory*, 109, 74
Struve, O., Sahade, J., Zebergs, V., & Lynds, B. T. 1958, *PASP*, 70, 267
van Genderen, A. M., et al. 1988, *A&AS*, 74, 467
Walborn, N. R. 1973, *AJ*, 78, 1067
Wiggs, M. S., & Gies, D. R. 1992, *ApJ*, 396, 238 (Paper II)