THE ASTROPHYSICAL JOURNAL, 242:1114–1123, 1980 December 15

ULTRAVIOLET, X-RAY, AND INFRARED OBSERVATIONS OF HDE 226868 = CYGNUS X-1

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Received 1979 November 1; accepted 1980 May 16

ABSTRACT

During 1978 April, May, and July, HDE 226868, the optical counterpart of Cygnus X-1, was repeatedly observed in the ultraviolet with the *IUE* satellite. Some X-ray and infrared observations have been made during the same period. The general shape of the spectrum is that expected from a late O supergiant. Strong absorption features are apparent in the ultraviolet, some of which have been identified. The equivalent widths of the most prominent lines appear to be modulated with the orbital phase. This modulation is discussed in terms of the ionization contours calculated by Hatchett and McCray, for a binary X-ray source in the stellar wind of the companion.

Subject headings: infrared: sources — line identifications — spectrophotometry — stars: individual — ultraviolet: spectra — X-rays: binaries

I. INTRODUCTION

Cygnus X-1, one of the strongest X-ray sources in the sky, was discovered by Bowyer *et al.* (1965). A radio counterpart was found by Braes and Miley (1971) and Hjellming and Wade (1971), following the report of fast variability by the *Uhuru* team (Oda *et al.* 1971). The identification in the optical is due to Webster and Murdin (1972) and Bolton (1972*a*), who showed that the 9 mag star HDE 226868, inside the radio error box, was a single-line binary with period $5^{d}.6$ and proposed that the invisible companion was a black hole.

High and low states with durations of years are observed in the X-rays with softer and harder spectra, respectively (e.g., Oda 1977). The transition is rather abrupt and probably associated with activity in the radio band. Absorption dips and troughs lasting $\sim\frac{1}{2}$ hr are observed sporadically near orbital phase 0 (for a review see Oda 1977).

Walborn (1973) has classified HDE 226868 as an O9.7 Iab (p var). The blue-violet absorption spectrum is normal. A peculiar feature is the variable emission line He II (λ4686), the radial velocity curve of which is shifted by about 120° with respect to that of its absorption lines (see Bolton 1972*b*, 1975; Walker, Young, and Glaspey 1978, and references therein). This line is observed in several X-ray sources and in the case of Cyg X-1 is interpreted to arise from the gas streaming onto the invisible secondary (Smith *et al.* 1973). Absorption in this stream is probably responsible for the X-ray dips.

Light variations were studied in detail (see Walker and Rolland Quintanilla 1978, and references therein) showing a double maximum light curve and an amplitude in the B band of 0.04 mag. No direct evidence of the presence of an accretion disk is available, and in fact it is not clear whether accretion onto the secondary

TABLE 1

BASIC PARAMETERS OF THE SYSTEM HDE 226868 = CYGNUS X-1

Parameter	Value
Spectral type	O9.7 Iab
T_{eff}	3×10^4 K
U	9.83 mag
B	9.68 mag
V	8.87 mag
J (1.24 μm)	6.79 mag
H (1.65 μm)	6.63 mag
K (2.22 μm)	6.50 mag
Distance	1.8 Kpc
Radius	18 R_0
Period	5.6 days
M	21 M_0
L	2.3×10^5 L_0
M_x	13 M_0
L_x	1.8×10^3 L_0

NOTE.—The data are taken from Bregman *et al.* 1973 and Conti 1978. The infared magnitudes are from our observations.

occurs through a disk or is spherical (see, e.g., Petterson 1978). Models of the X-ray emission have been constructed for both cases (for a review, see Lightman, Shapiro, and Rees 1978).

The basic parameters of the system are summarized in Table 1. For a detailed description of the Cyg X-1/HDE 226868 system, we refer to Oda (1977), Bahcall (1978), Conti (1978), and Eardley *et al.* (1978).

In this paper we report some UV observations of HDE 226868 taken with the *International Ultraviolet Explorer* (*IUE*; see § II), during the 2 weeks when the satellite was continuously dedicated to the study of X-ray sources. X-ray and IR observations taken at the same time are described in §§ III and IV. The results are discussed in § V. Here the UV spectrum is compared with Kurucz's (1979) model atmospheres, and the effect of X-ray heating on the wind of the primary is considered.

II. *IUE* OBSERVATIONS OF HDE 226868

a) *The Observations*

A general description of *IUE* and the data acquisition is given by Boggess *et al.* (1978*a*, *b*). The 14 low-resolution (~6 Å) spectra we examine here were produced at the Goddard station. A Journal of Observations is given in Table 2. Spectrum SWP 1273 was taken during the commissioning phase of activity of the *IUE* (Dupree *et al.* 1978).

Spectra SWP 1979 and 2049 have been reprocessed in order to correct for errors of the intensity transfer functions, following the procedure reported in *IUE/ESA Newsletter*, No. 4. The orbital phases are those derived by Kemp (1977) from optical photometry, with $P=5.600000\pm0.00024$ days and epoch 1976 January 26.745 UT for inferior conjunction of the primary.

The mean of the calibration curves produced by US and UK project groups (Bohlin *et al.* 1980) was used. The reduced spectra are given in Figures 1 and 2. Spectra LWR 1428 and 1439 (Figs. 2*e* and 2*f*) were taken with the small aperture diaphragm. In order to compare these latter spectra with the others, the fluxes were multiplied by a factor of 2, which is the normal light loss for that observing mode. However, because of the uncertainty of the procedure, these spectra have not been used for photometric purposes.

TABLE 2

JOURNAL OF OBSERVATIONS OF HDE 226868

Image	Aperture	Exposure (min)	Phase	Date of Observation (JD 2,440,000+)	Integral Flux (10^{-10} ergs cm^{-2} s^{-1}) 1250–1900 Å (SWP)	1950–2500 Å (LWR)
SWP 1273	large	40	0.93	3599.03	1.04	...
SWP 1445	large	50	0.32	3629.26	1.16	...
LWR 1425	large	15	0.43	3629.87	...	0.48
SWP 1451	large	50	0.44	3629.92	1.13	...
SWP 1460	large	45	0.62	3630.90	1.16	...
LWR 1428	large	10	0.62	3630.93	...	0.46
LWR 1428	small	10	0.63	3630.95	...	...
SWP 1478	large	45	0.97	3632.89	...	...
LWR 1439	large	10	0.98	3632.91	...	0.40
LWR 1439	small	10	0.98	3632.93	...	...
SWP 1515	large	45	0.05	3638.91	1.06	...
SWP 1979	large	45	0.27	3701.76	1.14	...
LWR 1819	large	9	0.28	3701.80	...	0.52
SWP 2049	large	50	0.54	3708.86	1.12	...

NOTE.—SWP: short-wavelength range 1150–2000 Å; LWR: long-wavelength range 1850–3350 Å; small aperture: 3″, circular; large aperture: 10″×20″, oval; orbital phases are taken from Kemp 1977.

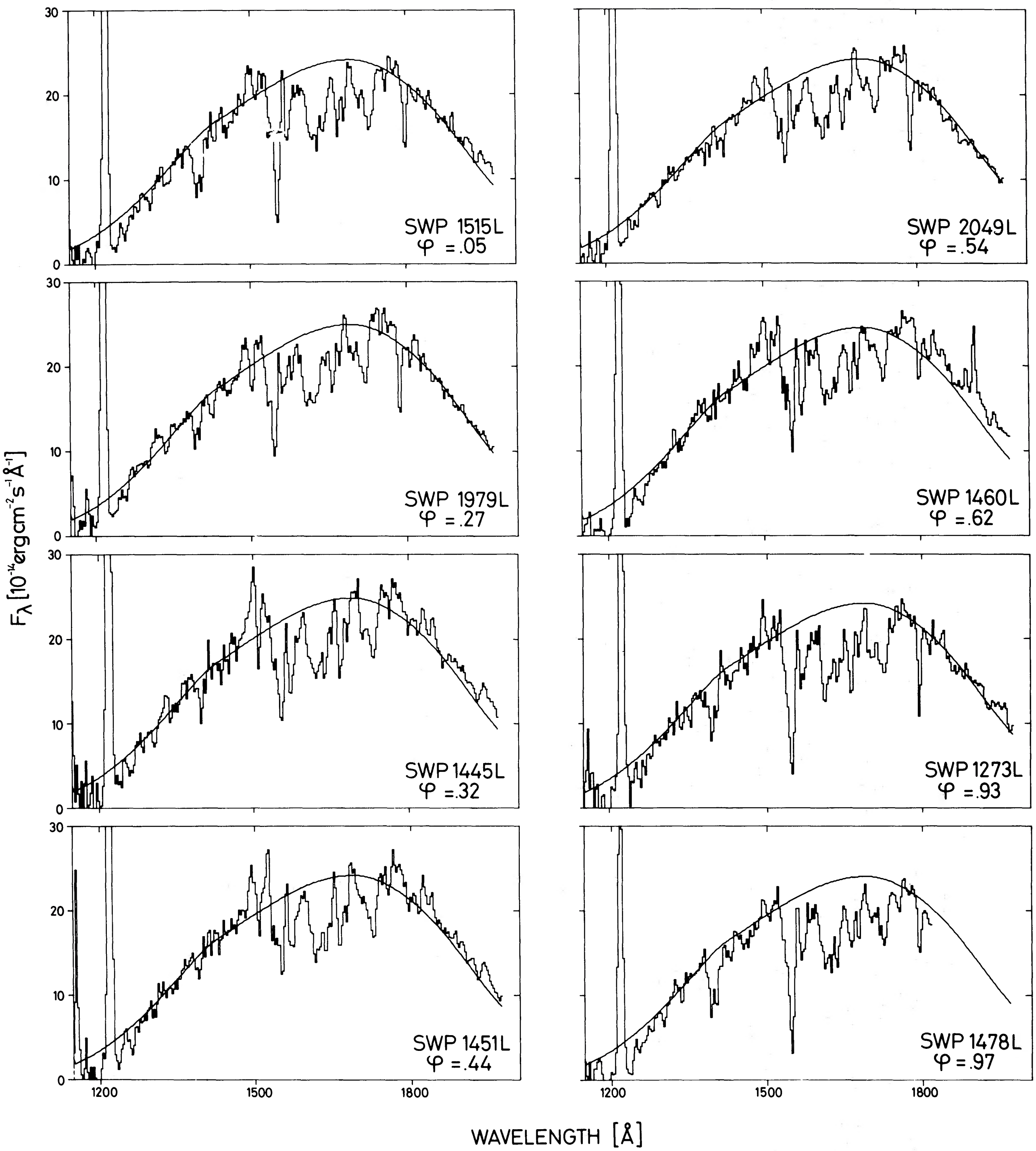

FIG. 1.—*IUE* spectra in the short-wavelength range. The solid lines represent reddened (E_{B-V}= 1.06) blackbody distributions with T=2.5×10^4 K. For each spectrum the image number and the orbital phase are given.

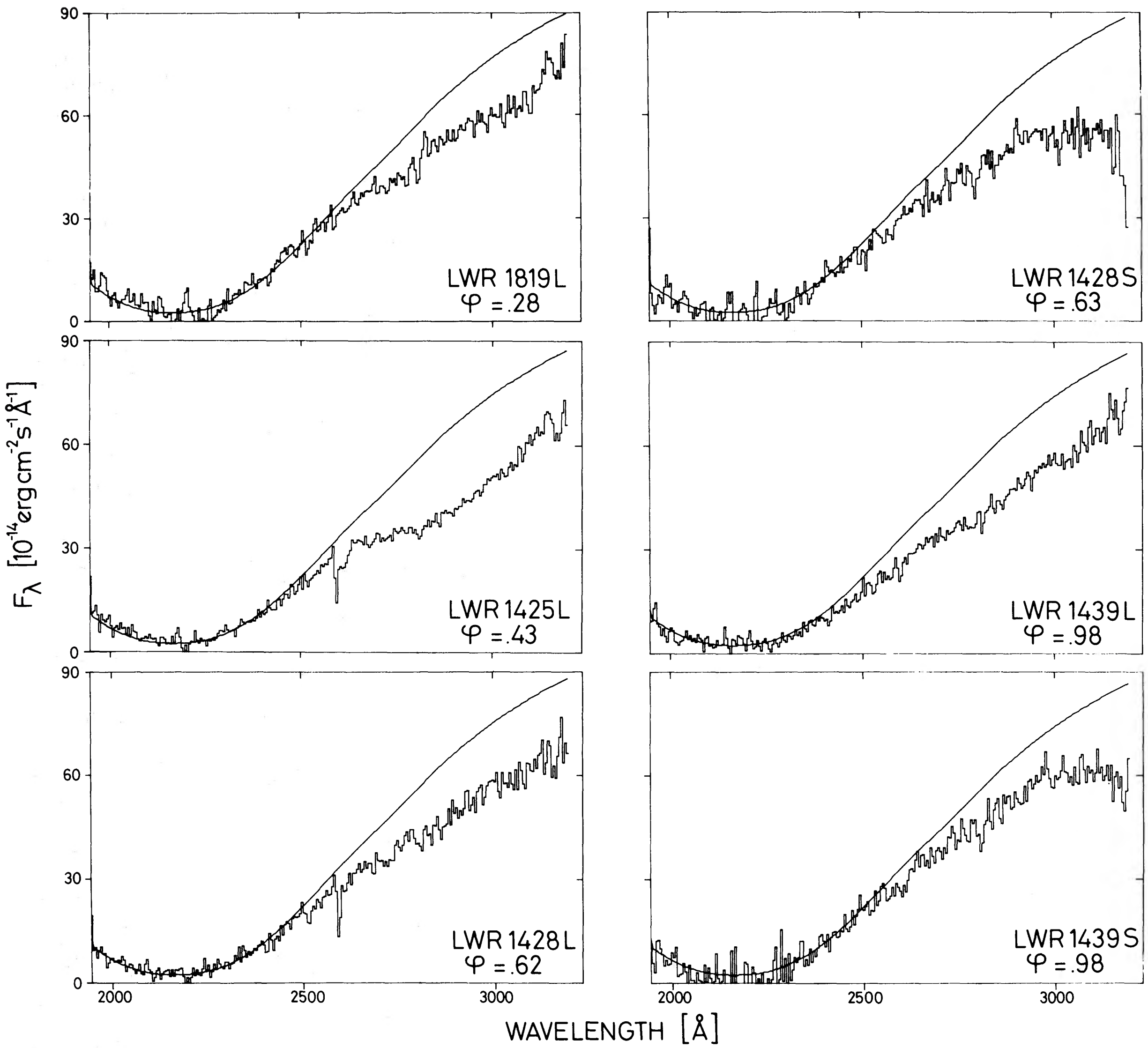

FIG. 2.—*IUE* spectra in the long-wavelength range. Spectra LWR 1428 and LWR 1439 have been taken with the small aperture and have been multiplied by 2 to compensate for light lost beyond the edges of the aperture. All spectra taken with the large aperture are partially saturated in the 2600–3200 Å region.

b) *The Continuum*

An examination of the spectra indicates the difficulty of estimating the continuum since many strong absorption features are present. As a guideline, we ploted, for each phase, a blackbody distribution with the fixed temperature $T=2.5\times10^4$ K (see Figs. 1 and 2), obtained normalizing to the B flux at the proper phase and fitting in two regions where absorptions are not prominent, namely in the intervals 1250–1350 Å, and 2350–2500 Å. The B light curve of Walker and Rolland Quintanilla (1978) (which exhibits a minimum to maximum variation of 4%) was used with the phases given by Kemp (1977). The reddening curve of Seaton (1979) is assumed with $E_{B-V}=1.06$, which is intermediate between the values respectively given by Bregman *et al.* (1973) and Wu, Van Duinen, and Hammerschlag-Hensberge (1975). The adopted temperature obviously depends on the assumed E_{B-V}. For example $E_{B-V}=1.02$ yields a temperature lower by 2000 K, while the temperature is increased by the same amount for $E_{B-V}=1.12$. This uncertainty is not really relevant, because the temperature derived in this way has no direct physical meaning, and the fitted

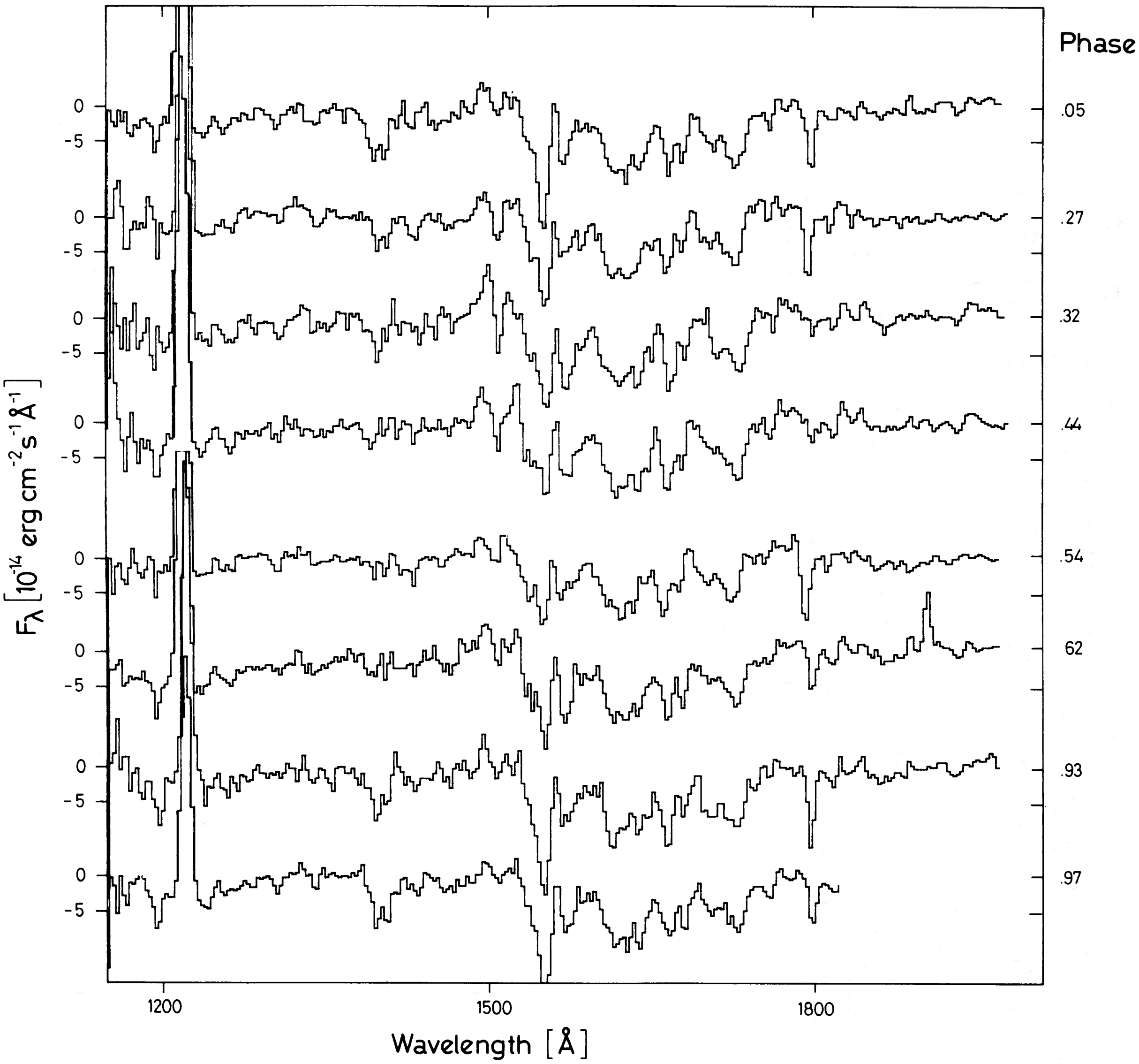

FIG. 3.—Rectified spectra in the short-wavelenth range. For each spectrum the zero level together with the ordinate scale are given.

blackbody distributions are used only for determining unambiguously the equivalent widths of the absorption lines.

In Table 2 we list the integrated fluxes in the 1250–1900 Å and 1900–2500 Å bands for the SWP and LWR exposures. The rms variation of these fluxes is ±5%—comparable to the ±3% reported by Bohlin *et al.* (1979), as the fluctuation in *IUE* observations of standard stars. However, the average of the integrated fluxes $F_{1250-1900}$ of the two short-wavelength spectra taken near phase 0 is $1.05 \pm 0.01 \times 10^{-10}$ ergs cm^{-2} s^{-1}, while the five spectra taken at other phases give a mean value of 1.14 ± 0.02. This suggests the existence of a minimum of the UV intensity around phase 0. The maximum to minimum variability is $8 \pm 2\%$. A similar variability is found also in the (1950–2500 Å) range where, however, we have fewer observations.

c) Lines

Figure 3 shows our short-wavelength rectified spectra, obtained by plotting the differences between the observed spectra and the blackbody curves of Figure 1. All spectra exhibit several absorption lines, some of which appear to be variable. In Table 3, the most prominent absorption features in the short-wavelength range are reported together with proposed identifications, recognizing that many of these are blends and will require high-resolution observations for positive

TABLE 3

STRONG ABSORPTION FEATURES AND PROPOSED IDENTIFICATIONS

Proposed Identifications	Measured Wavelengths (in Å) on SWP 1515
Si II λ1261; λ1265	1258
O I λ1302; λ1306	1306
C II λ1334, λ1336	1340
Not identified	1369
Si IV λ1394, λ1403	1396, 1406
Not identified	1450
Not identified	1481
(Fe II λ1507 and Fe III λ1505)?	1509
C IV λ1548, λ1550	1550
Blend of Fe II lines	1566 to 1575
Blend	1614 to 1624
He II λ1640	1638
(O III λ1663 and Fe II λ1671)?	1666
Not identified	1679
Not identified	1707
N IV λ1719 and Al II λ1719 to λ1725 .	1725
Not identified	1760

identification. The measured wavelengths refer to spectrum SWP 1515. Shifts in wavelength in other spectra are within the expected accuracy of the wavelength scale, i.e., no greater than 5 Å. In the long-wavelength spectra, strong lines are absent, and because of the poor resolution, identification becomes hazardous. An absorption feature probably corresponding to Mg II (λλ2796,2803) appears in all six spectra.

In Table 4, equivalent widths of the most prominent features are reported for each spectrum, using two different estimates of the continuum. The former (left columns) refers to the blackbody continuum (see Fig. 1), the latter (right columns) to a continuum fitted by eye. In both cases integration intervals taken into account are determined by eye.

One can note that the equivalent widths of Si IV and C_{IV} vary similarly with orbital phase, being largest around phase 0 (see Fig. 4). The intrinsic errors on each point are about 6% (2 σ reproducibility—Bohlin *et al.* 1979), but the main source of uncertainty is the choice of the continuum. This can affect significantly the value of single determinations but, as is apparent from Figure 4, not the general behavior.

The phase modulation of the equivalent widths of some absorption lines can explain at least part of the variability of the integrated fluxes reported above.

III. X-RAY OBSERVATIONS

Cyg X-1 was observed with the *Copernicus* satellite from JD 2,443,630.83 ($\phi=0.62$) to JD 2,443,635.96 ($\phi=0.53$), which covers *IUE* observations SWP 1460, SWP 1478, LWR 1428, and LWR 1439. A plot of the data is given in Figure 5. Each point represents approximately $1\frac{1}{2}$ hr integration of the background-

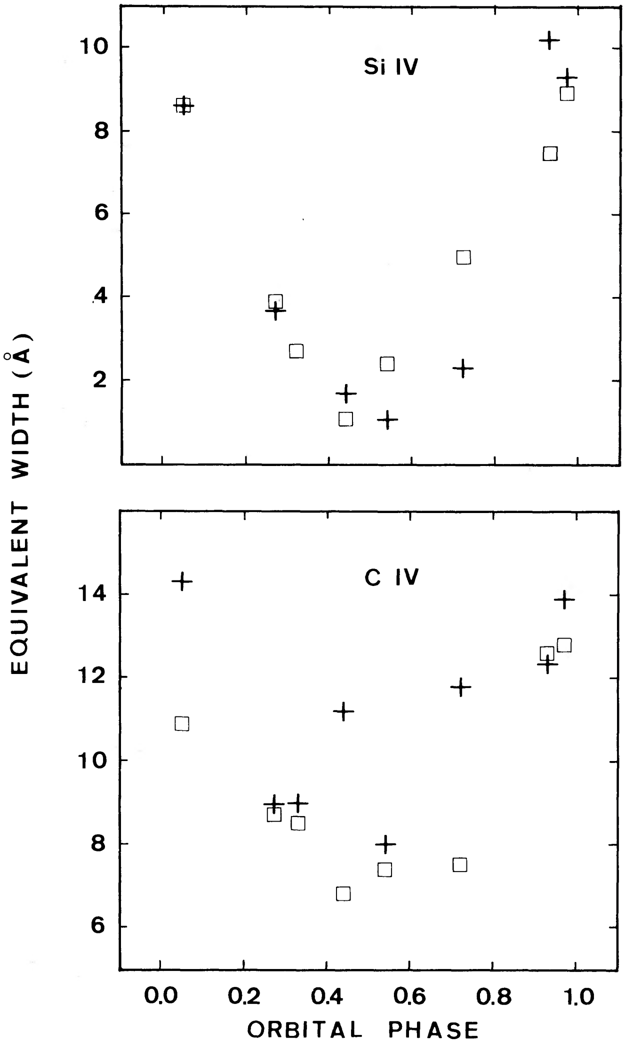

FIG. 4.—Equivalent widths of Si IV (*upper*) and C IV (*lower*) vs. orbital phase. Open squares correspond to the blackbody continuum, and crosses to a continuum fitted by eye.

corrected raw data (which has approximately 86 s sampling time). The error bars on the counts represents 1 σ. The detector energy range was 3.8–8.8 keV. The spectral hardness ratio (4.6–8.8 keV counts to 3.8–4.6 keV counts) is also shown as an indication of possible spectral changes. No significant change of the spectrum indicating increased photoelectric absorption was found, but just over 2 days into the observations, at $\phi=0$, there is a significant intensity drop which could be due to electron scattering. The observations show that the source was in a low state.

IV. INFRARED PHOTOMETRY OF CYGNUS X-1

Cyg X-1 was observed between 04:30 UT and 05:30 UT on 1978 May 1, when the phase was 0.41. This is very close to *IUE* observation SWP 1415. The *J*, *H*,

TABLE 4

EQUIVALENT WIDTHS OF SELECTED LINES

ION	SWP 1515		SWP 1979		SWP 1445		SWP 1451		SWP 2049		SWP 1460		SWP 1273		SWP 1478	
	phase 0.05		phase 0.27		phase 0.32		phase 0.44		phase 0.54		phase 0.62		phase 0.93		phase 0.97	
C II λλ1334,1336 and O IV 1338	2.1	3.5	0.9	2.4	0.5	4.4	0.8	...	1.1	0.9	1.2	2.1	1.0	4.8	0.5	1.9
Si IV λλ1394,1403	8.6	8.6	3.9	3.7	2.7	...	1.1	1.7	2.4	1.1	0.5	2.3	7.5	10.2	8.9	9.3
C IV λλ1548,1550 and Fe III λ1540.....	10.9	14.3	8.7	8.9	8.5	9.0	6.8	11.2	7.4	8.0	7.5	11.8	12.6	12.4	12.8	13.9
Fe II λ1564 to λ1575 ...	3.3	5.1	3.1	4.2	4.1	3.5	3.1	4.3	3.3	4.2	3.7	3.0	4.1	6.4	4.3	3.5
O III λ1663 and Fe II λ1671	6.6	4.1	4.5	3.5	5.4	3.5	5.5	3.9	5.6	4.2	5.5	2.1	7.6	4.2	7.5	3.6

NOTE.—Equivalent widths, in Å, measured with reference to a blackbody continuum (left columns) and to a continuum fitted by eye (right columns).

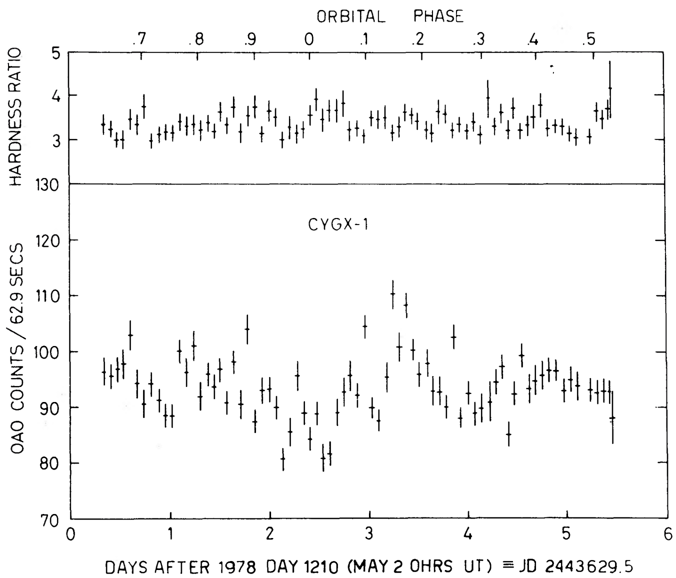

FIG. 5.—X-ray intensities of Cyg X-1; *Copernicus* counts and hardness ratios. The upper abscissa scale gives the orbital phase.

and K wavelengths were centered at 1.24 μm, 1.65 μm, and 2.22 μm, respectively. The calibration star was α Bootis. The measured magnitudes are reported in Table 1. The 1 σ accuracy is 1%. The magnitudes were derived using the absolute calibration of Thomas, Hyland, and Robinson (1973) and Gehrz, Hackwell, and Jones (1974). Values of A_λ/E_{B-V} in the near-infrared were obtained from the studies of OBA stars by Schultz and Wiemer (1975), Whittet, von Breda, and Glass (1976), and Sneden *et al.* (1978). Our data, dereddened for $E_{B-V}=1.06$ are consistent with a Rayleigh-Jeans spectrum and so may be interpreted as the long-wavelength tail of the photospheric emission spectrum of the O9.7 star.

For a distance modulus of 12 (Bregman *et al.* 1973), the absolute magnitude at 2.22 μm becomes $-5.9\pm$ 0.11, i.e., about 50% brighter than that quoted by Becklin *et al.* (1972). However, they do not quote their adopted values for distance modulus or interstellar reddening, and so little significance can be attributed to this difference.

V. DISCUSSION

In Figure 6, the UV spectra SWP 1515 and LWR 1439 have been combined in order to compare the general shape of the UV spectrum around phase 0, when the primary is in front of the X-ray source, with the two model atmospheres which, in the grid calculated by Kurucz (1979), are closer to the spectral classification of the primary. Curve *a* represents Kurucz's model for $T_{\rm eff}=30{,}000$ K and surface gravity $\log g=3.5$, and curve *b* corresponds to $T_{\rm eff}=25{,}000$ and $\log g=3.0$. In order to obtain a satisfactory agreement with data, a reddening $E_{B-V}=1.12$ and $E_{B-V}=1.06$, respectively, for the two models has been adopted with the reddening curve by Nandy *et al.* (1976) for the Cygnus region. The comparison is limited to $\lambda > 1400$ as the reddening curve is given only for these wavelengths.

The UV absorption features are typical of those observed in supergiants of similar spectral type (Panek and Savage 1976; Nandy 1977; Code 1977; Code and Meade 1979). In particular Panek and Savage (1976) give for supergiants between O9 and B0 equivalent widths of 9 Å and of 12 Å for Si IV (λ1400) and C IV (λ1550), respectively. Our measurements of Si IV at phase 0 are in good agreement with the above value, while at phase 0.5 the equivalent width is 3 Å. C IV, which in our measurement may be contaminated by Fe III (λ1540), does not vary as strongly with phase. Its equivalent width around phase 0 is again close to that given by Panek and Savage (1976).

An interpretation of the phase dependence of the equivalent widths (Fig. 4) can be given in terms of the discussion by Hatchett and McCray (1977) of X-ray heating on stellar winds.

In particular they show that an X-ray source produces a region of high ionization which moves with the X-ray source. When this region is in front of the primary ($\phi=0.5$), the intensity of the absorption lines is minimum, because of depletion of the absorbing ion species, while the opposite occurs at $\phi=0$.

In the Hatchett and McCray (1977) model the wind is taken as spherically symmetric around the primary, and the X-ray source is emitting isotropically. In the optically thin case the ionization structure is determined

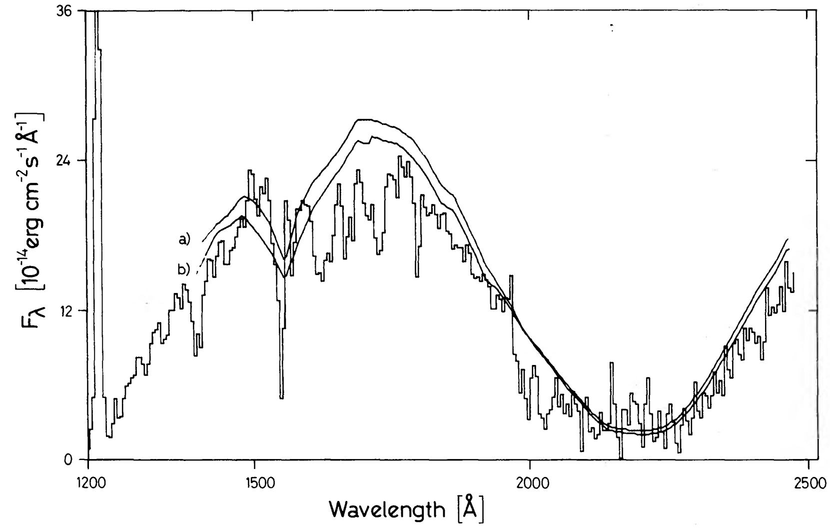

FIG. 6.—Comparison of the measured UV spectrum around phase 0 with Kurucz's model atmospheres. Curve *a* is for $T_{eff}=30{,}000$ K, log $g=3.5$, and $E_{B-V}=1.12$. Curve *b* is for $T_{eff}=25{,}000$ K, log $g=3.0$, and $E_{B-V}=1.06$.

by the single parameter $\xi=L_X/n(r_x)^2$, where L_X is the luminosity of the X-ray source, r_x is the distance from the X-ray source, and n is the number density. It may be useful to use the dimensionless parameter $q=\xi/\xi_0$, where $\xi_0=L_x/n_0 d^2$, d is the distance of the center of the primary from the X-ray source, and n_x is the density at the X-ray source. Assuming a constant velocity wind, the loci of constant q are spheres with centers on the straight line connecting the centers of the two stars. Their radius is $dq^{\frac{1}{2}}(1-q)^{-1}$, and the centers are located on the side closer to the X-ray source for $q<1$, or closer to the primary of $q>1$. Hatchett and McCray (1977) show that the surfaces of the constant column density are in good approximation spheres congruent to those of constant q. Within this simplified picture one expects that the line intensity modulation is symmetric around phase 0.5 (see Fig. 4).

We now discuss the extension of the region transparent to the C IV and S IV lines, following the paper by Dupree *et al.* (1980) on Vela X-1. First, one must estimate the total depth τ of the wind. Our low-resolution UV spectra do not allow a direct estimate of $\dot{M}$. Taking $\dot{M}\approx 2.5\times10^{-6}$ $M_\odot$ yr^{-1}, as suggested by Hutchings (1976) on the basis of observations in the visible, and a wind velocity $V\approx1600$ km s^{-1} (Conti 1978) one derives $\tau=4\times10^{22}$ cm^{-2}. The optical depths for C IV and Si IV absorptions are therefore $\tau_{C\,IV}=8\times10^3\,X_{C\,IV}$ and $\tau_{Si\,IV}=1.5\times10^3\,X_{Si\,IV}$, where $X_{C\,IV}$ and $X_{Si\,IV}$ are the fraction of carbon and silicon in the given state of ionization. Therefore the regions where $X_{C\,IV}<5\times10^{-4}$ and $S_{Si\,IV}<2.5\times10^{-4}$ are certainly transparent to the wavelengths corresponding to the C IV and Si IV lines. From the calculations by Hatchett, Buff, and McCray (1976) and preliminary results by Kallmann and McCray (1979) one knows that the above concentrations correspond to log $\xi=1.7$ and log $\xi=1.2$ for C IV and Si IV, respectively. Taking an X-ray luminosity $L_X\approx1.8\times10^3$ $L_\odot$, a separation $d\approx43$ $R_\odot$, and $n_0\approx6\times10^9$ cm^{-3}, one has $q\approx0.4$ for C IV and $q\approx0.1$ for Si IV. The values of q correspond to transparent regions lying both outside the conical shadow of the primary and also outside a radius of 43 $R_\odot$ for C IV and 16 $R_\odot$ for Si IV.

This result indicates that the region transparent to Si IV is more extended than that transparent to C IV, in agreement with our observations, which show that departure of the equivalent widths from that of an undisturbed star are larger for Si IV than for C IV. The shape of the opaque and transparent regions discussed above should be considered as a first approximation, since there are several reasons why the values of q can differ from the calculated ones. The largest uncertainty is in the adopted value of the wind parameters in the hypothesis that the wind is spherically symmetric around the primary without being influenced by the X-ray source. The gas streaming mentioned in the Introduction (§ I), connected with the X-ray absorption dips is in fact an indication of the roughness of the spherical approximation. Moreover, the Cyg X-1 X-ray spectrum is significantly different from the bremsstrahlung spectrum with $kT=10$ keV considered by Hatchett, Buff, and McCray (1976).

If the overall picture is correct, following Hatchett and McCray (1977), we would expect the shape of P Cyg profiles to depend on the orbital phase. The investigation of this requires observations at high dispersion, as was done for the much brighter system Vela X-1 = HD 77581 by Dupree *et al.* (1980).

Finally, we recall that the observations reported in this paper were taken during the low state of the X-ray source (see § III). Since the high state corresponds to a higher soft X-ray luminosity, one expects variability of temperature and density, of the plasma surrounding the primary, which should affect the UV spectral lines.

A comparison of the UV observations in the two states should therefore by of great interest.

We would like to thank F. Middelburg and K. Banse for their help in the use of the ESO Interactive Image Processing Package.

The authors also gratefully acknowledge the support—both technical and financial—from NASA, ESO, and SRC. Much of the travel and research costs were supported by grants and contracts from these agencies. In addition, they furnished the spacecraft, the ground support facilities, and a standard preliminary reduction of all data onto magnetic tape and photographic reconstructions of the images. We especially acknowledge the assistance of the *IUE* Observatory staff, both at Greenbelt and at VILSPA, and in particular of the NASA resident astronomers, F. Espenak, A. Holm, P. Perry, F. Schiffer, and C. C. Wu, for their assistance in the acquisition and reduction of these data.

REFERENCES

Bahcall, J. 1978, in *Physics and Astrophysics of Neutron Stars and Black Holes*, ed. R. Giacconi and R. Ruffini, (Amsterdam: North Holland).
Becklin, E. E., *et al.* 1972, *Nature Phys. Sci.*, **239**, 130.
Boggess, A., *et al.* 1978*a*, *Nature*, **275**, 372.
_____. 1978*b*, *Nature*, **275**, 377.
Bohlin, R. C., Holm, A. V., Savage, B. D., Snijders, M. A. J., and Sparks, W. M. 1980, *Astr. Ap.*, submitted.
Bolton, C. T. 1972*a*, *Nature*, **235**, 271.
_____. 1972*b*, *Nature Phys. Sci.*, **240**, 124.
_____. 1975, *Ap. J.*, **200**, 269.
Bowyer, S., *et al.* 1965, *Science*, **147**, 394.
Braes, L. L. E., and Miley, G. K. 1971, *Nature*, **232**, 246.
Bregman, J., *et al.* 1973, *Ap. J. (Letters)*, **185**, L117.
Code, A. D. 1977, *Highlights Astr.*, **4**, 325.
Code, A. D., and Meade, M. R. 1979, *Ap. J. Suppl.*, **39**, 195.
Conti, P. S. 1978, *Astr. Ap.*, **63**, 225.
Dupree, A. K., *et al.* 1978, *Nature*, **275**, 400.
_____. 1980, *Ap. J.*, **237**, 163.
Eardley, D. M. *et al.* 1978, *Comments Ap.*, **7**, 151.
Gehrz, R. D., Hackwell, J. A., and Jones, T. W. 1974, *Ap. J.*, **191**, 675.
Hatchett, S., Buff, J., and McCray, R. 1976, *Ap. J.*, **206**, 847.
Hatchett, S., and McCray, R. 1977, *Ap. J.*, **211**, 552.
Hjellming, R. M., and Wade, C. M. 1971, *Ap. J. (Letters)*, **168**, L21.
Hutchings, J. P. 1976, *Ap. J.*, **203**, 438.
Kallmann, T., and McCray, R. 1979, private communication.
Kemp, J. C. 1977, *IAU Circ.*, 3149.
Kurucz, R. L. 1979, *Ap. J. Suppl.*, **40**, 1.
Lightman, A. P., Shapiro, S. L., and Rees, M. J. 1978, in *Physics and Astrophysics of Neutron Stars and Black Holes*, ed. R. Giacconi and R. Ruffini (Amsterdam: North Holland).
Nandy, K. 1976, *Astr. Ap.*, **51**, 63.
_____. 1977, *Highlights Astr.*, **4**, 289.
Oda, M. 1977, *Space Sci. Rev.*, **20**, 757.
Oda, M., *et al.* 1971, *Ap. J. (Letters)*, **166**, L1.
Panek, J. R., and Savage, B. D. 1976, *Ap. J.*, **206**, 167.
Petterson, J. A. 1978, *Ap. J.*, **224**, 625.
Seaton, M. J. 1979, *M.N.R.A.S.*, **187**, 73p.
Schultz, G. V., and Wiemer, W. 1975, *Astr. Ap.*, **43**, 133.
Smith, H. E., Margon, B., and Conti, P. S. 1973, *Ap. J. (Letters)*, **179**, L125.
Sneden, C., *et al.* 1978, *Ap. J.*, **223**, 168.
Thomas, J. A., Hyland, A. R., and Robinson, G. 1973, *M.N.R.A.S.*, **165**, 201.
Walborn, N. R. 1973, *Ap. J. (Letters)*, **179**, L123.
Walker, E. N., and Rolland Quintanilla, A. 1978, *M.N.R.A.S.*, **182**, 315.
Walker, G. A. H., Young, S., and Glaspey, J. W. 1978, *Ap. J.*, **226**, 976.
Webster, B. L., and Murdin, P. 1972, *Nature*, **235**, 37.
Whittett, D. C. B., von Breda, I. G., and Glass, I. S. 1976, *M.N.R.A.S.*, **177**, 625.
Wu, C. C., Van Duinen, R. J., and Hammerschlag-Hensberge, G. 1975, in *X-Ray Binaries*, NASA SP-389.

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