THE ASTROPHYSICAL JOURNAL, 265:354–362, 1983 February 1

ULTRAVIOLET SPECTROSCOPY OF V1341 CYGNI (=CYGNUS X-2)[1]

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Received 1982 February 11; accepted 1982 July 21

ABSTRACT

Cyg X-2 is a low-mass X-ray binary of orbital period $P = 9\overset{d}{.}8$. Several *International Ultraviolet Explorer* (*IUE*) spectra in the 1200–3000 Å range either obtained by us or taken from *IUE* archives are examined. Variability up to a factor of 2 is apparent. Although the data are insufficient for a study of the phase modulation, one can exclude a strong maximum at the inferior conjunction of the X-ray source (phase 0). From the rectification of the 2200 Å absorption dip, a color excess $E_{B-V} = 0.45 \pm 0.05$ is derived. A discussion of the emission-line spectrum yields estimates of the temperature ($T \approx 2 \times 10^4$ K), density ($n \approx 2 \times 10^{10}$ cm^{-3}), and radius ($r \approx 5 \times 10^{12}$ cm) of the line-emission region. According to standard models, the intrinsic UV emission from the accretion disk should be negligible with respect to the observed continuum. Two processes may contribute to its production. One is reprocessing of X-rays in the accretion disk, consistent with the suggestion by Lyutyj and Sunyaev and Ziółkowski and Paczyński that the disk must be thick in order to screen off the primary from the X-ray flux. The other process is bremsstrahlung of a hot plasma producing the X-rays. A comparison with the phenomenology of Sco X-1, whose similarity with Cyg X-2 has been noted, suggests that the two processes are likely to coexist.

Subject headings: stars: accretion — stars: individual — ultraviolet: spectra — X-rays: binaries

I. INTRODUCTION

Cyg X-2 belongs to the class of binary X-ray sources with low-mass companions. Although its optical identification with the variable star V1341 Cyg dates from 1967, a reliable determination of the binary period, $P = 9\overset{d}{.}843$, has been given only recently (Cowley, Crampton, and Hutchings 1979, hereafter CCH; Crampton and Cowley 1980). The likely parameters of the system are given in Table 3 of CCH.

The absence of X-ray eclipses in most members of the class of low-mass X-ray binaries (Joss and Rappaport 1979), which was puzzling for many years, is now generally interpreted as an indication of the existence of thick accretion disks, which screen off the X-ray emission when the inclination angle is close to 90° (Milgrom 1978; Lewin and Joss 1981).

Ultraviolet observations are of particular importance for a direct study of the properties of the disk, the emission of which in the visible may be confused with that of the noncollapsed secondary. Since Cyg X-2 is one of the few members of the class within the capabilities of the *International Ultraviolet Explorer* (*IUE*), it is therefore of great interest.

In this paper spectra of Cyg X-2 obtained with *IUE* by us as well as spectra collected from *IUE* archives are analyzed with a homogeneous procedure and discussed. Some spectra have already been presented elsewhere (Maraschi, Tanzi, and Treves 1980; Chiappetti *et al.* 1981).

II. OBSERVATIONS

All spectra examined here were obtained in the large aperture of the spectrometer on board *IUE*, in the low-resolution mode ($\Delta\lambda \approx 6$ Å). Epoch, exposure time, and orbital phase (from the elements determined by Crampton and Cowley 1980) are given in Table 1 for each observation. The phase convention attributes phase 0 to periastron, which very nearly corresponds to inferior conjunction of the X-ray source. All spectra have been reduced using the procedure developed at ESO and with the calibration curve of Bohlin *et al.* (1980). Each spectrum has been checked against camera defects and ion events by inspection of the line-by-line extracted spectrum. Spectra SWP (short-wavelength prime) 5247 and 5248 have been reprocessed in order to correct for errors in the intensity transfer function following the procedure indicated in *IUE*/ESA Newsletter, number 4.

Integral fluxes in selected wavelength intervals are reported in Table 1 for each spectrum. Although the intervals are chosen in order to exclude strong emission lines, a nonnegligible line contribution can still be present. Integral fluxes of the continua, as defined in Figures 1 and 2, are also given. Between the highest and the lowest values, corresponding to orbital phases 0.3 and 0.6, respectively, the flux variation is of a factor of 2. In the optical region the maximum observed variability is also of a factor of 2, superposed on a much weaker phase-dependent modulation ($\Delta m \approx 0.2m$) (Lyutyj and Sunyaev 1976; CCH). In the X-ray band erratic variability is of the same order, while no phase-dependent

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[1] Based on observations with the *International Ultraviolet Explorer* collected at Villafranca Satellite Tracking Station of the European Space Agency (VILSPA) and on *IUE* archived data.

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TABLE 1

JOURNAL OF *IUE* OBSERVATIONS

				INTEGRAL FLUX (10^{-12} ergs cm^{-2} s^{-1})							
IMAGE NO.	EXP. TIME (min)	EPOCH (JD) 2,444,000. +	PHASE	1280–1320	1490–1530	1680–1720	1840–1880	2400–3000	1200–1900 Continuum	2000–3000 Continuum	SOURCE OF SPECTRA
SWP 5247	180	9.875	0.121	0.20	0.25	0.18	0.17	...	3.4	...	*IUE* archives
SWP 5248	200	10.013	0.135	0.21	0.19	0.16	0.15	...	3.0	...	*IUE* archives
LWR 5816	90	159.104	0.280	...	...	...	...	2.3	...	3.4	*IUE* archives
SWP 6844	190	159.172	0.287	0.33	0.26	0.33	0.24	...	4.6	...	Maraschi *et al.* 1980
SWP 6877	180	162.206	0.595	0.18	0.10	0.16	0.14	...	2.3	...	Maraschi *et al.* 1980
LWR 7379	180	331.958	0.840	...	...	...	...	3.4	...	4.8	*IUE* archives
LWR 7380	205	332.041	0.848	...	...	...	...	3.6	...	4.8	*IUE* archives
LWR 7393	418	332.958	0.941	...	...	...	...	2.0	...	2.8	*IUE* archives
LWR 9572	150	598.841	0.961	...	...	...	...	2.5	...	2.8	This paper
SWP 10889	440	599.050	0.972	0.26	0.23	0.24	0.22	...	3.8	...	This paper

NOTE.—The fluxes in selected wavelength intervals are given for each observation, together with the flux in the 1200–1900 Å bands corresponding to the continua of Fig. 1 and the flux in the 2000–3000 bands corresponding to the continua of Fig. 2.

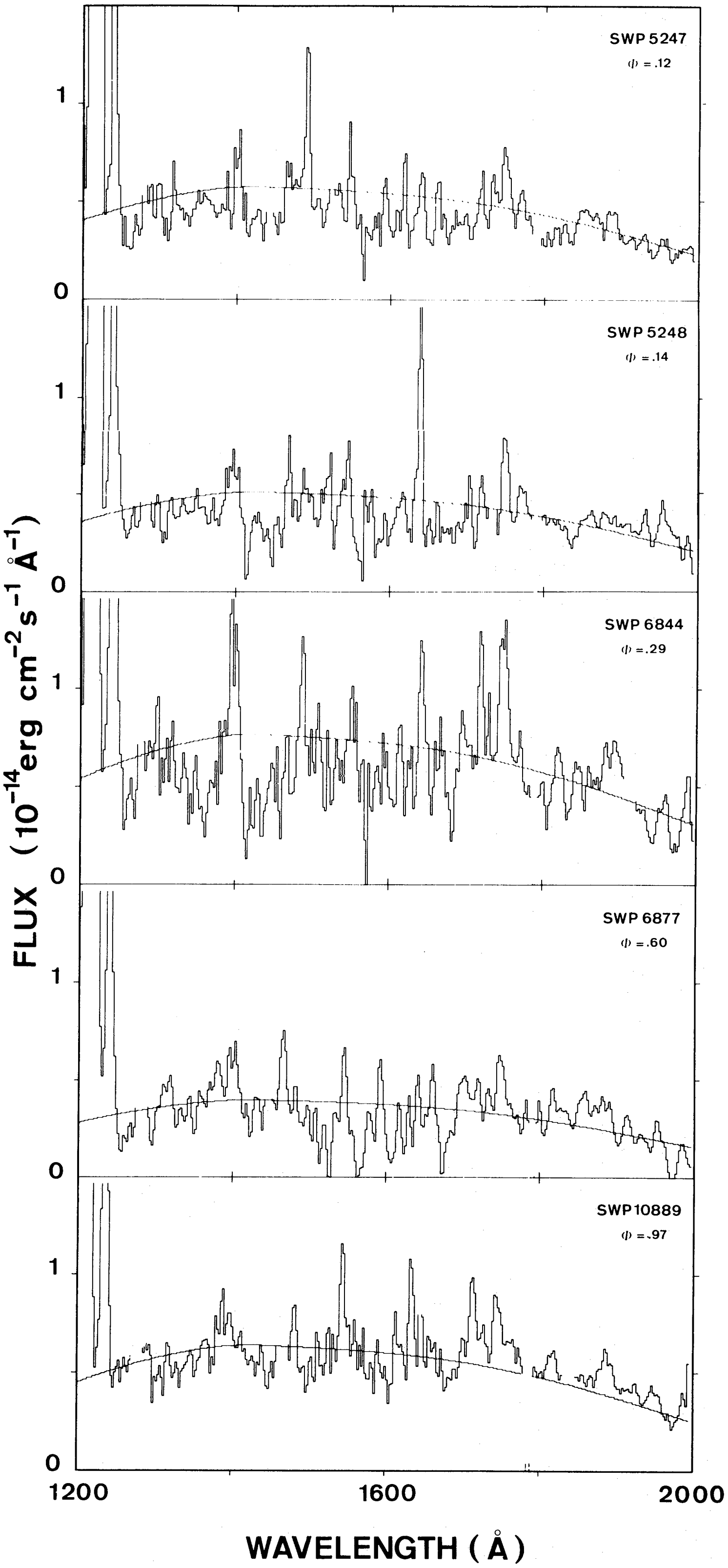

FIG. 1.—Spectra of Cyg X-2 in the short-wavelength range of *IUE* at different orbital phases. The continua were obtained by fitting the spectra with a reddened ($E_{B-V} = 0.45$) power law $F_\lambda \propto \lambda^{-\alpha}$, with $\alpha = 2.2$.

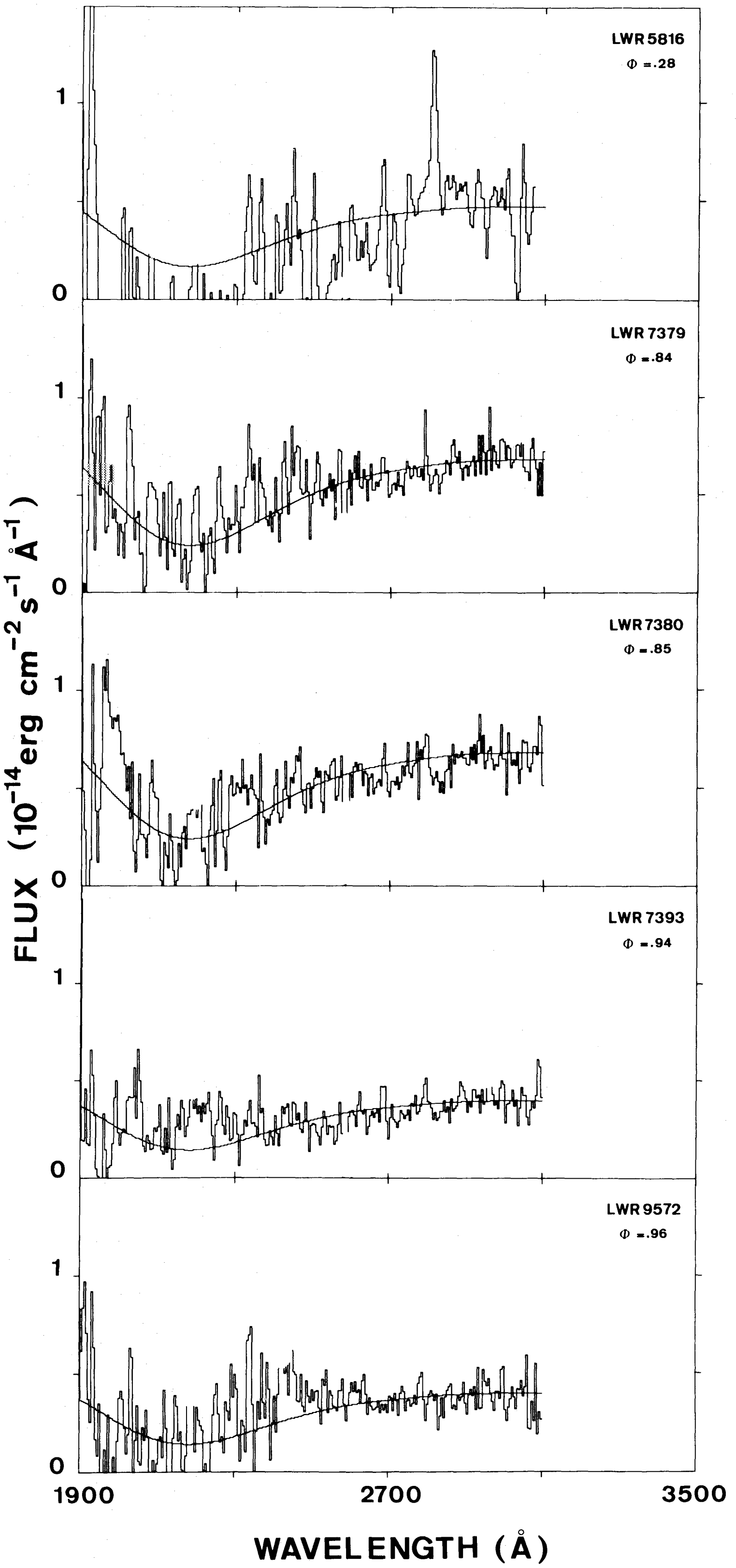

FIG. 2.—Spectra of Cyg X-2 in the long-wavelength range of *IUE* at different orbital phases. The continua were obtained as in Fig. 1

modulation is observed (Giacconi *et al.* 1972; Parsignault and Grindlay 1978). Any conclusion about a possible phase modulation in the UV is premature, since the phase coverage is scarce and the variation of a factor 1.8 occurring within a day (cf. LWR [long-wavelength redundant] 7380 and LWR 7393) indicates large erratic variability. No pronounced maximum around phase 0 is apparent, thus indicating that X-ray heating of the late-type star does not contribute appreciably to the ultraviolet emission.

Figures 1 and 2 present the ultraviolet spectra discussed in this paper.

III. INTERSTELLAR EXTINCTION

In Figure 3 the spectrum resulting from the combination SWP 10889 and LWR 9572, obtained successively at orbital phase 0, is dereddened with various values of E_{B-V}, using the mean galactic reddening curve by Seaton (1979). A good rectification of the 2200 Å dip is obtained for $0.4 \leq E_{B-V} \leq 0.5$, which, for $R = 3.2$, gives $1.3 \leq A_V \leq 1.4$, somewhat larger than the value proposed by Lyutyj and Sunyaev (1976) on the basis of optical data. In the following we shall take $E_{B-V} = 0.45$, i.e., $A_V = 1.4$.

In the X-rays a low-energy cutoff is observed and appears to be variable with corresponding hydrogen column density between 3×10^{21} and 10^{22} atoms cm^{-2} (Branduardi 1977; Persignault and Grindlay 1978). The lower value is consistent with the extinction derived from the ultraviolet data, assuming $A_V \approx 5 \times 10^{-22}$ N_H (Bohlin 1975; Gorenstein 1975; Ryter, Cesarsky, and Adouze 1975).

IV. THE LINE SPECTRUM

In all short-wavelength spectra the dominant line is N v (λ1240), while C iv (λ1550) is, in all cases, weak

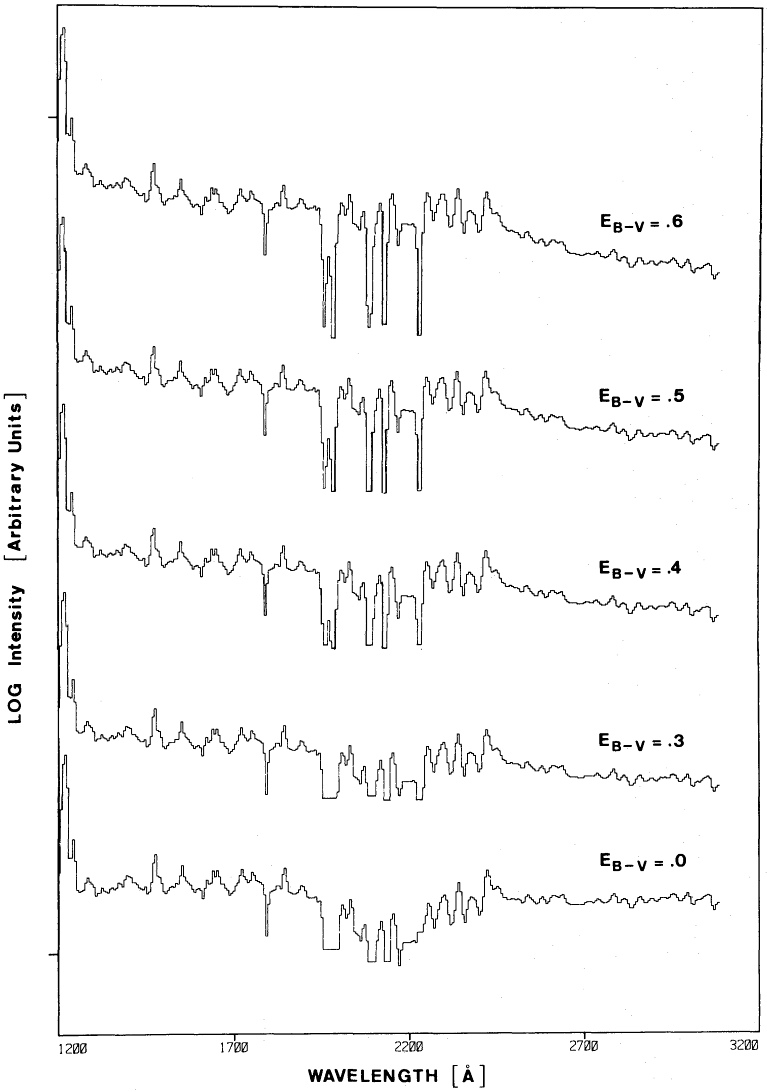

FIG. 3.—The combined spectrum SWP 10889 + LWR 9572 taken at phase 0 is dereddened for different values of E_{B-V}

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with respect to N v. Other lines which are always present are Si IV (λ1400), He II (λ1640), N III (λ1718). These lines are present in each of the five short-wavelength spectra. A list of lines detectable at each phase with possible identifications is given in Table 2.

The presence of different ionization states of nitrogen reinforces the suggestion made by Maraschi, Tanzi, and Treves (1980) that the weakness of C IV with respect to N v may be due to an abundance anomaly rather than to peculiar physical conditions. This is also observed in other X-ray binaries like AE Aqr and, in a lesser degree, in Sco X-1 and Her X-1 (Jameson, King, and Sherrington 1979; Willis *et al.* 1980; Gursky *et al.* 1980).

A calibration of the temperature and ionization equilibria in a homogeneous gas sphere with a central X-ray source with a bremsstrahlung spectrum of $kT = 10$ keV has been carried out by Hatchett, Buff, and McCray (1976). In this model the luminosity in the resonance doublet of N v is predominantly due to collisional excitation and is produced in a region where the ionization parameter $\xi = L/(nr^2) \approx 100$, and the temperature $T \approx 10^4$ K. As a first approximation one can apply this model to the case of Cyg X-2 in order to derive order-of-magnitude estimates of the physical parameters of the N v region. From the ratio of the strength of N v (λ1240), assumed also in this case to be mainly collisionally excited, to N IV (λ1718), which should derive mainly from recombination (see Nussbaumer and Schild 1981), one can derive an estimate of the temperature. In fact, with these assumptions the intensity ratio of the two lines is given by

$$R_{1240/1718} = \frac{I(1240)}{I(1718)} = \frac{q_{\rm sp}(1240)}{\alpha_{\rm eff}} \frac{1718}{1240}, \qquad (1)$$

where $q_{\rm sp} = 3 \times 10^{-7} T_4^{-1/2} \exp(-11.59/T_4)$ cm^3 s^{-1} is the collisional excitation coefficient, and $\alpha_{\rm eff}$ is the effective recombination coefficient from N v to N IV, which varies from 3.5×10^{-12} cm^3 s^{-1} at 10^4 K to 3×10^{-12} cm^3 s^{-1} at 1.5×10^4 K (Storey 1981). The observed average ratio, dereddened with $E_{B-V} = 0.45$, is $R_{1240/1718} = 10$, from which we get $q_{\rm sp} = 2.0$–2.5×10^{-11} cm^3 s^{-1}, corresponding to $T = 1.2 \times 10^4$ K. This is consistent with the adopted model. From the luminosity of the N v line we can then derive

$$\langle n_e^2 \rangle V = \frac{L_{1240}}{h\nu_{1240} q_{\rm sp} f_V A_{\rm N}}, \qquad (2)$$

where $A_{\rm N}$ is the nitrogen abundance, and f_V is the fraction in the fourth ionized state. Assuming the solar

TABLE 2

EMISSION AND ABSORPTION LINES OF CYGNUS X-2 IN THE SHORT-WAVELENGTH RANGE OF *IUE* (1200–1900 Å)

Identification	S5247 λ (Å)	$\phi = 0.12$ EW (Å)	S5248 λ (Å)	$\phi = 0.14$ EW (Å)	S6844 λ (Å)	$\phi = 0.29$ EW (Å)	S6877 λ (Å)	$\phi = 0.6$ EW (Å)	S10889 λ (Å)	$\phi = 0.97$ EW (Å)
Emission Lines										
N v ($\lambda\lambda$1239, 1243)	1241	34	1239	37	1241	51	1239	43	1239	31
Si IV ($\lambda\lambda$1393, 1402)	1398 1409	9	1385 1405	10	1395 1402	27	1396 1404	14	1393 1403	10
Not identified	1468	...	1468	...	1467	...	1467	...	1473	...
N IV (λ1486.5)	1490	...	weak	...	1489	...	...	...	1488	...
C IV ($\lambda\lambda$1548, 1550)	1549	...	1546	...	1551	...	1546	...	1550	...
He II (λ1640)	1644	8	1639	...	1643	14	1640	7	1640	8
N IV (λ1718.5)	1717	7.5	1718	5	1720	8	1717	5	1719	6
N III ($\lambda\lambda$1747–1754)	1752	15	1748	18	1750	16	1747	11	1750	7
Absorption Lines										
S II (λ1260), Si II (λ1260)	1260	...	1259	...	1257	...	1256	...	1252	...
Not identified	1417	...	1416	...	1415	...	1414	...	1412	...
C I (λ1561), Fe II (λ1564)	1568	...	1564	...	1572	...	1567	...	...	...
Not identified	...	...	...	...	1682	...	1675	...	1684	...

NOTE.—The feature at 1750 Å may be contaminated by active pixels (Hackney, Hackney, and Kondo 1982). In the 2000–3000 Å range, because of the poor signal-to-noise ratio, the only reliable identification is Mg II ($\lambda\lambda$2798, 2803), which appears in emission in spectrum LWR 5816.

abundance $A_N = 10^{-4}$ and $f_V = 1$, from $L_{1240} = 10^{34}$ ergs s^{-1} one estimates

$$\langle n_e^2 \rangle V \approx 3 \times 10^{59} \text{ cm}^{-3} . \quad (3)$$

Another relation between electron density and dimension comes from the assumption of the ionization parameter $\xi = L/(nr^2) \approx 100$. For an X-ray luminosity $L_X = 6 \times 10^{37}$ ergs s^{-1}, one derives $r = 5 \times 10^{12}$ cm and $n \approx 2 \times 10^{10}$ cm. With this value of the density the collisional de-excitation of the level originating N IV (λ1487) becomes important, and this could explain the relative weakness of this line in our spectra. The derived set of values is based upon using the ionization parameter as in the thin case. The effects of opacity calculated in Hatchett, Buff, and McCray (1976) modify the scaling procedure. However, these effects should be small since the parameter values are very close to those used in model 2 of Hatchett, Buff, and McCray (1976). A more important approximation is that of spherical geometry. For cylindrical symmetry with height smaller than the radius, higher values of n and smaller values of r would be obtained.

V. THE CONTINUOUS SPECTRUM

The combined spectrum obtained at phase 0, dereddened with $E_{B-V} = 0.45$, is well fitted (Fig. 4) by a power law $F_\lambda = \lambda^{-\alpha}$, with $\alpha = 2.2$. The ± 0.05 uncertainty on E_{B-V} gives a ± 0.2 uncertainty on the spectral index.

The overall energy distribution is shown as F_ν versus ν in Figure 4, where observations at different wavelengths refer to different epochs.

A reddening correction corresponding to $E_{B-V} = 0.45$ has been applied to the data from the infrared to the ultraviolet. The X-ray data have not been corrected for absorption, which, for $N_H = 10^{22}$ cm^{-2}, should be small above 2 keV.

The overall spectrum is remarkably similar to that of Sco X-1. Both sources have a thermal X-ray emission, Cyg X-2 with $kT \approx 4$ keV, Sco X-1 with $kT \approx 7$ keV. The UV to X-ray intensity ratio is also similar, and the UV continua are in both cases very flat. With respect to the UV, the optical emission is more prominent in Cyg X-2 than in Sco X-1. This may be partly due to the continuum contributed by the nondegenerate companion star (see Fig. 5), the absorption lines of which are visible in Cyg X-2, while they are undetected in Sco X-1.

The UV spectrum of Sco X-1 has been interpreted by Willis *et al.* (1980) in terms of bremsstrahlung emission from a hot plasma cloud surrounding the collapsed object, as originally proposed for the optical emission of Sco X-1 (Chodil *et al.* 1968; Neugebauer *et al.* 1969; Felten and Rees 1972; Illarionov and Sunyaev 1972). In view of the similarity of the overall energy distribution, this model is adequate also for Cyg X-2 (see Fig. 5). However, no physical arguments have been given to justify the existence of the cloud.

A different model, proposed by Milgrom (1976*a*, *b*) and by Milgrom and Katz (1976) for both Sco X-1 and Cyg X-2, attributes the ultraviolet emission to the late-type secondary heated by the X-rays. Previous ultraviolet observations of Cyg X-2 in the range 1000–2000 Å at orbital phases 0.3 and 0.6 seemed consistent with the model (Maraschi, Tanzi, and Treves 1980). The new data discussed in this paper, which cover several orbital phases and extend up to 3000 Å, contrast with the model, because there is no indication of a maximum in the UV light curve at phase 0. Moreover, the spectrum in the 1200–3000 Å range dereddened with $E_{B-V} = 0.45$, differs considerably from the expectations of the model. The lack of substantial heating of the primary is indicated also by the light curve in the B and V bands (CCH), which are double peaked and can be interpreted as ellipsoidal variations. Photometry in the U band, taken at an epoch of high X-ray intensity, shows a single-peaked light curve; this, together with the variation of the spectral type, indicates that heating of the primary is not entirely negligible. However, for an inclination angle of 70° (CCH) and an isotropic X-ray flux, one would expect a much larger effect.

The weakness of heating effects on the secondary can

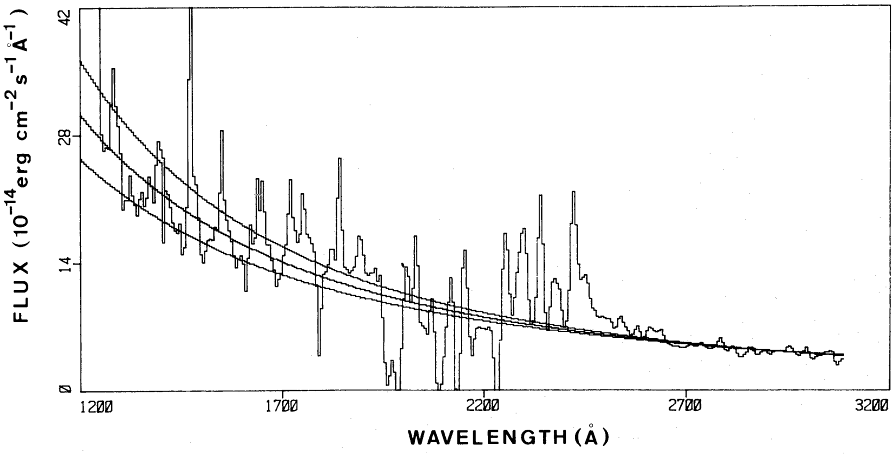

FIG. 4.—Fit of the combined spectrum SWP 10889 + LWR 9572 dereddened with $E_{B-V} = 0.45$, with different power laws. *From top to bottom*, $\alpha = 2.4, 2.2, 2.0$.

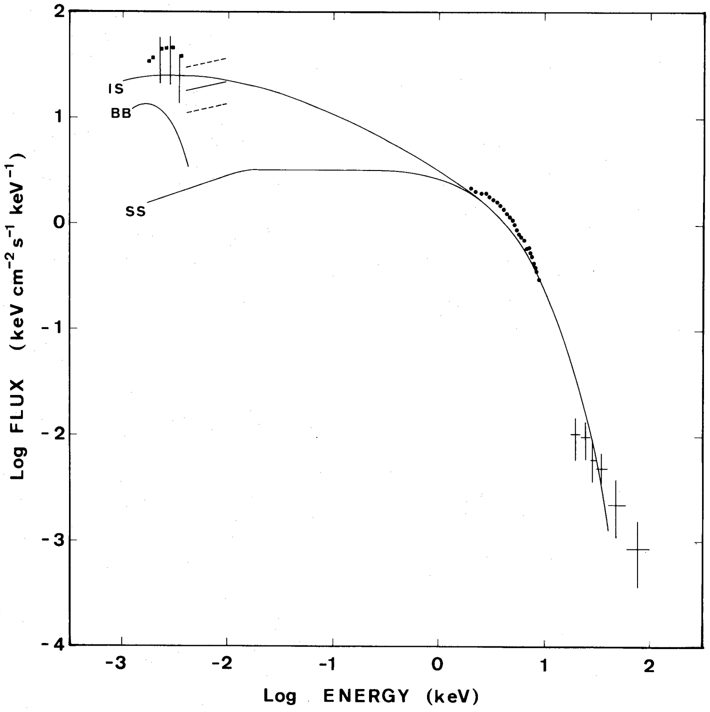

FIG. 5.—Overall spectrum of Cyg X-2. The squares represent the photometry by Peimbert *et al.* (1968). The vertical bars indicate the range of variability of the *UBV* photometry by Lyutyj and Sunyaev (1975). The *IUE* observations at phase 0 are shown as a solid line; the dashed lines encompass the range of variability. The 2–9 keV X-ray fluxes are from *Ariel 5* data (Branduardi 1977); typical variability in this range is of a factor of 2. Hard X-ray fluxes are taken from Maurer *et al.* (1982). The spectrum of the nondegenerate star is represented by a blackbody distribution (*BB*) with $T = 7 \times 10^3$ K and $R = 7.4\ R_\odot$ at a distance of 8 kpc. The curves labeled *IS* and *SS* are the theoretical continua computed by Illarionov and Sunyaev (1972) and Shakura and Sunyaev (1973) for a hot cloud and an accretion disk with Comptonization parameter $y = kT\tau_T{}^2/m_e c^2 = 0.1$ and viscosity parameter $\alpha = 10^{-2}$, respectively, normalized at 9 keV.

be attributed to the presence of a thick accretion disk, which screens off, at least partially, the primary from the X-ray source (Lyutyj and Sunyaev 1976; Ziółkowski and Paczyński 1980). A large fraction of the X-rays should then be reprocessed by the disk and reemitted at lower frequencies. We examine whether the optical and UV emission may originate in this process.

If we attribute the dereddened flux $F_h = 3.3 \times 10^{-10}$ ergs cm^{-2} s^{-1} from 1000 to 5000 Å entirely to this effect, the solid angle subtended by the disk is

$$\Omega = \frac{\pi}{\cos i}\frac{F_h}{F_X}\eta^{-1} = 0.7\eta^{-1}\,, \qquad (4)$$

where η is the fraction of geometrically intercepted X-rays which are actually absorbed. The angle subtended by the primary is $\theta = 0.55$ and is equal to $\Omega/2\pi$ for $\eta = 0.2$. This value of η is acceptable and may be a lower limit if the reprocessed flux also contributes shortward of 1000 Å. The reprocessing region should span a range of temperatures from 10^4 to 4×10^4 K in order to explain the flat spectrum from the optical to the UV. These correspond to sizes of 10^{12} to 10^{11} cm, somewhat smaller than the line-emission region. Therefore, the explanation of the origin of the optical and UV emission as reprocessing of X-rays in an accretion disk seems entirely consistent.

The intrinsic emission of the disk in the optical and UV bands calculated according to standard disk models (Shakura and Sunyaev 1973; Pringle and Rees 1972), normalized to the observed X-ray flux, is negligible with respect to the observed total optical and UV emission (see Fig. 5). The closeness of the spectral shape of the UV to that of the emission from the optically thick region of an accretion disk ($F_\nu \propto \nu^{1/3}$) could therefore be coincidental.

Finally, we maintain the arguments against the white dwarf model of Cyg X-2 (Branduardi *et al.* 1980), based on the absence of reflection of a conspicuous soft X-ray emission.

VI. CONCLUSIONS

The present observations are consistent with two modes of production of the UV continuum: X-ray reprocessing in a disk at $T \approx 4 \times 10^4$ K or bremsstrahlung tail of a hot region ($T \approx 10^7$ K) responsible for the X-ray emission.

The presence of X-ray reprocessing in the disk is well established by rapid simultaneous photometry in the optical and X-ray bands for Sco X-1 (Ilovaisky *et al.* 1980; Petro *et al.* 1981 and references therein) and for a number of low-mass binaries (van Paradijs 1981). On the other hand, in the low state, no correlation between the optical and X-ray flux of Sco X-1 is observed. This implies that at least two mechanisms are required for explaining its optical emission. Note that in the cloud model the X-ray and optical fluxes can be anticorrelated if the optical depth increases at constant temperature (Illarionov and Sunyaev 1972). For a direct study of X-ray reprocessing in Cyg X-2, observations of the same kind would be needed. The absence of a strong modulation of the emission of the primary and the presence of UV lines already indicate that X-ray reprocessing occurs in the outer region of the disk ($T \approx 10^4$ K) also in Cyg X-2. The hot region emitting through the bremsstrahlung process ($T \approx 10^7$ K) could be related to X-ray reprocessing occurring very near the neutron star, where the disk could be substantially blown up by radiation pressure. The two models would then represent the two extremes of the same process.

We wish to thank the staff at VILSPA for skillful assistance during the observations. Useful discussions with H. Nussbaumer and N. Panagia on the line spectrum are gratefully acknowledged. We are also indebted to the European Southern Observatory for use of the Interactive Image Analysis System.

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