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THE OBSERVATIONS OF THE X-RAY SOURCE HZ HERCULIS/HERCULES X-1

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ABSTRACT

The results of a campaign of monitoring HZ Her with the *IUE* satellite are presented. The spectrum and light variation outside of eclipse are consistent with the Milgrom and Salpeter model for emission from the X-ray heated photosphere of the primary. Near eclipse there is UV flux in excess of the prediction of the heated photosphere model, which shows significant 35 day variations and is consistent with an origin in a precessing disk, as described by Gerend and Boynton.

The spectrum shows the strong emission lines of N V and C IV, which generally vary in the sense of the continuum. The N V/C IV ratio is greater than 2 near orbital phase 0.5 and approaches unity near eclipse. It is suggested that these emission lines are optically thick and arise from both the heated photosphere and the accretion disk.

Subject headings: stars: individual — X-rays: binaries

I. INTRODUCTION

The X-ray source Her X-1 was discovered by Tananbaum *et al.* (1972) from observations with the *Uhuru* satellite. Their early data revealed a complex pattern of X-ray behavior: a 1.24 s pulsation, a 1.7 day binary period, and a 35 day ON-OFF cycle. So-called "pre-eclipse dips" with a period of 1.6 days have also been found in more recent observations (e.g., Crosa and Boynton 1980). Liller (1972) and Bahcall and Bahcall (1972) identified HZ Her as the optical counterpart of Her X-1 on the basis of photometric variations with the same period and phase. Davidsen *et al.* (1972) also succeeded in detecting the 1.24 s pulsations optically.

The "standard model" for the binary system incorporates a Roche-lobe–filling A7 V star (Oke 1976) and a neutron star secondary, the primary being heated in the region of the inner Lagrangian point by X-rays from the vicinity of the secondary. The apparent optical spectral type and broad-band magnitudes of the primary vary from about early B to late A (Crampton and Hutchings 1972) and by $\Delta m_B \approx 1.5$ mag (e.g., Chevalier and Ilovaisky 1974). The bulk of the optical emission appears to be caused by X-ray heating of the primary photosphere (Milgrom and Salpeter 1975, hereafter MS); however, variations in the light curve around the 35 day period have been convincingly identified with the effect of a precessing accretion disk around the neutron star (Petterson 1975; Gerend and Boynton 1976, hereafter GB).

In this paper we report the preliminary results of a program of ultraviolet spectrophotometry based on data from the *International Ultraviolet Explorer* (*IUE*) collected at the Goddard Space Flight Center of the

National Aeronautic and Space Agency and the Villafranca Satellite Tracking Station of the European Space Agency. The observations were made as part of a collaboration between the groups involved from the three agencies controlling the satellite: the National Aeronautics and Space Administration (USA), the Science Research Council (UK), and the European Space Agency.

HZ Her was observed from *IUE* on 20 different occasions, scattered around the orbital phase, and mostly close to the time of onset of the X-ray emission during the 35 day phase. The number of observations is small compared to what has been accumulated at visual wavelengths. However, we are able to correlate our data with known features in the light curve. Furthermore, because of the high temperature present in the system, the UV observations are important for testing models of the emission and for determining its origin.

II. OBSERVATIONS

HZ Her was observed with the low-dispersion mode of the *IUE* satellite. The bulk of the exposures were taken (cf. Tables 1 and 2) with the short-wavelength (SWP) camera, covering the spectral region 1150–1950 Å with a resolution of ~6 Å; a few exposures were also taken with the long-wavelength (LWR) camera, covering the region 2000–3200 Å. All spectra were obtained with the large aperture (10″ × 20″) in order to ensure accurate spectrophotometry; in some cases, two exposures were taken in the large aperture to save camera preparation time. Further details of the spacecraft and instrumentation are given by Boggess *et al.* (1978*a*, *b*).

In Figure 1 we display typical spectra of HZ Her, similar to those reported by Dupree *et al.* (1978). The very strong Lα feature is geocoronal in origin. The dominant features are the N V λ1240 and C IV λ1550 emission lines superposed on a relatively flat, featureless continuum. He II λ1640 is also present at a weak level. There is evidence for S IV λ1394 and 1403 emission as well. O V λ1371, N IV λ1719, and N III 1750 may be present but are not apparent in all spectra. The peaks at λ1400, λ1640, and λ1720 in Figure 1 (SWP 1516), for example, are estimated at 2.5–3 σ. Several spectra show evidence of interstellar lines at 1300 Å (probably O I λ1302.17 and 1304.86), and 1335 Å (C II λ1334.53).

The typical long-wavelength spectrum is a featureless continuum, slightly more intense at 2000 Å than at 3000 Å. A few long-wavelength spectra show evidence of weak interstellar absorption lines at 2380 Å (Fe II λ2382.003), 2595 Å (Fe II λ2599.40), and 2800 Å (Mg II λ2795.5). HZ Her is at high galactic latitude, and interstellar reddening is known to be small. We find no sign of the 2200 Å interstellar absorption feature (cf., Nandy *et al.* 1975), requiring that $E_{B-V} < 0.05$ mag.

In Tables 1 and 2 we list the continuum and line fluxes. All data were reduced using the absolute calibration of Bohlin *et al.* (1978) based on comparisons between the *IUE* measurements and photometric data from the *TD 1 52/68*, *OAO 2*, and *ANS* satellites.

III. DISCUSSION

a) *Continuum*

We shall examine our data in the framework of GB (see also Deeter *et al.* 1976), because their phenomenological model provides the most comprehensive explanation of the many features of the optical light curve

TABLE 1

HZ HERCULIS OBSERVING LOG (SHORT WAVELENGTH)

SWP	$t_{exp.}$ (minutes)	Midpoint JD 2,443,000+	ϕ (1.7 days)	ψ (35 days)	X-ray ON-OFF	F(N V)[a]	F(C IV)[a]	F(1500)[b]
1436	103	628.21	0.000	0.818	OFF	...	...	...
	35	709.82	0.001	0.157	ON	~0.5	~0.1	~0.016
2057	35	709.91	0.054	0.160	ON	~0.6	~0.6	~0.033
	60	704.86	0.084	0.015	ON	5.0	3.8	0.80
2014	60	704.91	0.113	0.017	ON	8.6	5.7	0.86
2058	35	709.98	0.095	0.162	ON	0.65	1.13	0.043
1432	150	626.75	0.141	0.776	OFF	3.6	2.3	0.23
1506	120	637.18	0.276	0.075	ON	8.3	4.4	0.87
1516	60	639.01	0.352	0.127	ON	14.9	6.0	1.35
1962	45	700.41	0.466	0.888	ON	10.3	5.8	1.59
1963	80	700.49	0.514	0.890	ON	SAT	6.4	1.67
1526	45	641.19	0.635	0.190	OFF	16.8	4.5	1.51
1272	90	598.90	0.761	0.977	ON	9.4	4.1	0.54
1988	60	702.63	0.772	0.095	ON	12.4	8.6	0.88
1511	120	638.21	0.882	0.104	ON	4.3	3.7	0.14
	35	709.73	0.948	0.155	ON	~1.2	~0.7	~0.04
2056	35	709.77	0.972	0.156	ON	~0.4	~1.0	...
SWR 1056	240	565.28	0.986	0.013	ON	...	...	0.03

[a] Flux in 10^{-13} ergs cm^{-2} s^{-1}.
[b] Flux in 10^{-13} ergs cm^{-2} s^{-1} Å^{-1}.

TABLE 2

HZ HERCULIS OBSERVING LOG (LONG WAVELENGTH)

LWR	$t_{exp.}$ (minutes)	Midpoint JD 2,443,000+	ϕ (1.7 days)	ψ (35 days)	X-ray ON-OFF	$F_{\lambda 2400}$[a]	$F_{\lambda 3000}$[a]
1405	130	626.87	0.212	0.779	OFF	0.46	0.32
1811	40	700.44	0.484	0.888	ON	0.81	0.56
1826	40	702.59	0.749	0.950	ON	0.48	0.35
1455	40	636.47	0.858	0.054	ON	0.23	0.17
1416	120	628.10	0.935	0.814	OFF	0.056	0.063

[a] Flux in 10^{-13} ergs cm^{-2} s^{-1} Å^{-1}.

of HZ Her. GB begin from the demonstration that the optical variations show a remarkable symmetry with the 35 day period, which they attribute to the emission from a precessing, tilted accretion disk. We also make use of predictions of MS based on the heated photosphere model.

In the following we adopt the GB convention of the 35 day cycle, where phase ψ is used to indicate phase within the 35 day cycle, and $\psi = 0.85$ is the X-ray turnon. An average period of 34.875 days (Holt *et al.* 1979) was used with turnon at JD 2,442,652.7 (Giacconi *et al.* 1973). The orbital phase ϕ is defined by $\phi = 0$ at mid–X-ray eclipse. These phases are listed in Tables 1 and 2. Continuum fluxes at 1500 and 3000 Å are plotted in Figures 2 and 3 as a function of orbital phase. The problem with testing the disk emission hypothesis is that our data do not span a very wide range in ψ. Corresponding to the disk at its most open-faced aspect as seen from Earth $\psi \approx 0$, 0.5; at $\psi \approx 0.25$, 0.75, the disk is approximately edge-on. We have somewhat arbitrarily divided the plotted data in the figures into two groups, with triangles representing $0.9 < \psi < 0.1$ and circles corresponding to data outside these phases.

The solid line in Figures 2 and 3 is the predicted variation in flux from MS. Figure 2 shows good agreement near quadrature between our data and the predictions of MS; however, there are discrepancies near $\phi \approx 0.5$ and $\phi \approx 0$.

The data near $\phi = 0.5$ were all taken near $\psi = 0.89$. GB have shown that there is a pronounced dip in the optical light curves for this combination of orbital and 35 day phases, due to the occultation of the primary by the disk, which is the possible cause of the discrepancy in the data from the MS model near $\phi = 0.5$. Similarly, the excess flux near eclipse may be attributed to the disk. The anomalously high points between $\phi = 0.8$ to 0.9 were taken at $\psi = 0.015$–0.095, where the disk has maximum visibility and where the visible light curve exhibits broad shoulders at quadrature.

Figure 4 is a plot of the short- and long-wavelength continuum spectrum near $\phi = 0.5$. For comparison we have shown the fluxes predicted by MS, assuming that X-ray heating of the primary star's photosphere is responsible for all of the emission. Given the coarseness of the wavelength bins in the calculation, the agreement is fairly good, particularly since no normal model atmosphere comes close to reproducing the entire spectrum.

The success of MS in predicting both the flux levels and the spectral shape outside of eclipse makes it reasonably certain that the X-ray heated primary atmosphere is the dominant component of the ultraviolet emission. The second component of light present in the system that is responsible for the excess emission near eclipse can be attributed to an accretion disc, as has been discussed by Strittmatter *et al.* (1973), Crampton and Hutchings (1972), Gerend and

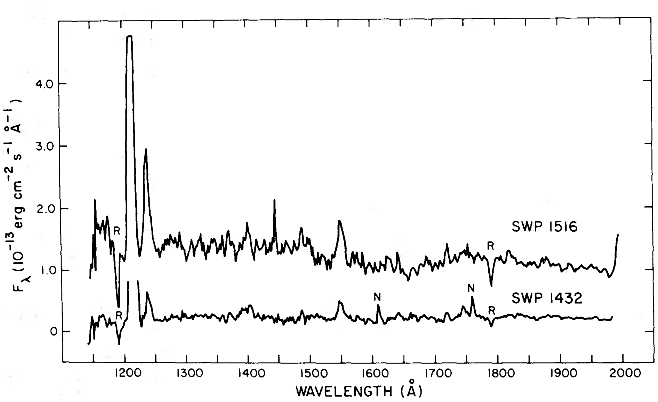

FIG. 1.—Typical short-wavelength *IUE* spectra of HZ Her: SWP 1432 ($\phi = 0.143$) and SWP 1516 ($\phi = 0.350$). Spectrograph fiducial marks (reseaux) are indicated by R. Radiation-induced noise spikes are indicated by N.

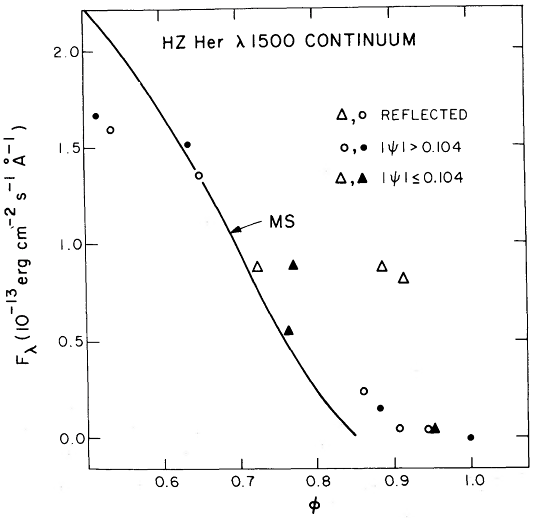

FIG. 2.—Comparison of the observed and predicted light curves of HZ Her near 1500 Å reflected around $\phi = 0.5$.

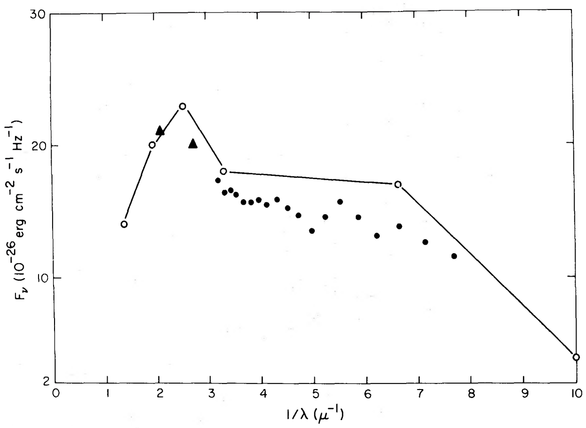

FIG. 4.—Comparison of the observed and predicted spectra of HZ Her near maximum light. *Filled circles*: SWP 1962, LWR 1811 *IUE* data ($\phi \approx 0.475$). *Triangles*: *U*, *B* data. *Open circles*: MS model prediction.

Boynton (1976), and Bisnovatyi-Kogan *et al.* (1977). However, Wilson (1973) suggested that this excess flux was due to circulation flows driven by the X-ray heating, resulting in the presence of emitting gas not directly heated by X-rays. Joss, Avni, and Bahcall (1973) invoked an extended gaseous emitting region; this suggestion gains plausibility from the work of Alme and Wilson (1974), who showed that X-ray heating of the primary can drive a substantial stellar wind (MS assume hydrostatic equilibrium).

In order to examine the two components of light more closely, we fit a power-law distribution ($f_\nu \approx \nu^\alpha$, where f_ν is in units of ergs cm^{-2} s^{-1} Hz^{-1}) to the short-wavelength continuum data. The results are shown in Figure 5 as a function of orbital phase. Below $\phi \approx 0.8$ the spectra are consistent with a single power law with $\alpha = -1.2$; as expected from the data in Figure 4, this is close to the value obtained for the MS spectrum, which has $\alpha \approx -1$. Beyond $\phi = 0.8$, the spectra deviate significantly from this single shape. The points at $\phi = 0.86, 0.88$ (SWP 1432 and 1511) are clearly different from each other and from the value 1.2. Points nearer eclipse were not plotted because of even worse statistical accuracy.

It is apparent from Figure 2 that beyond an orbital phase of $\phi \approx 0.85$ (<0.15), the major contribution to the light from the system originates on the disk. Cherepaschuk, Goncharskii, and Yagola (1977) (hereafter, CGY) and Bisnovatyi-Kogan *et al.* (1977) have derived average parameters for the disk by following the evolution of the optical colors through eclipse. With our limited data base, we cannot do this, especially because of the complication of changing aspect caused by precession and of reduced area caused by eclipse. But as noted above, there are two data points (SWP 2014) taken near $\psi = 0$ where it appears that the full disk is in view. Furthermore, the

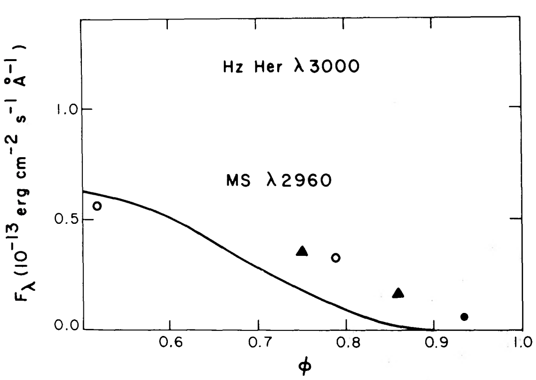

FIG. 3.—Comparison of the observed and predicted light curves of HZ Her near 3000 Å reflected around $\phi = 0.5$.

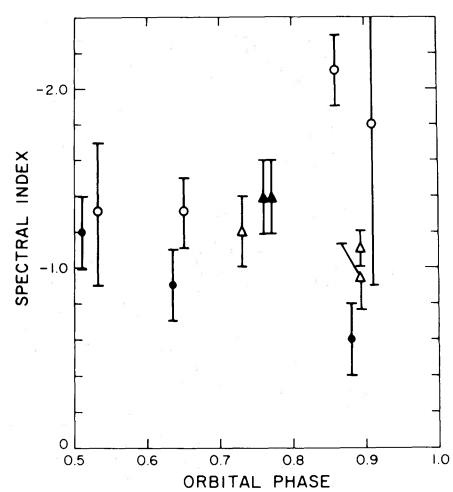

FIG. 5.—Variation of spectral index at short wavelengths with orbital phase.

orbital phase is such that only ≈20% of the disk is eclipsed. We can use these data to make a consistency check.

The CGY model has an average disk temperature of 22,000 K and a radius of 10^{11} cm. Our data at short wavelength, in fact, are consistent with such a temperature. Taking the CGY numbers and adopting a distance of 5 kpc to HZ Her, we calculate a flux at 1500 Å of 8×10^{-14} ergs cm^{-2} s^{-1} $Å^{-1}$ for the whole disk, compared to an observed value of 8.6×10^{-14} ergs cm^{-2} s^{-1} $Å^{-1}$ at $\phi = 0.113$. The degree of agreement is probably fortuitous, but still provides an important confirmation of the essential elements of the CGY model.

The variations in α seen in Figure 5 may be indicative of a temperature distribution across the disk; then, depending on ψ and ϕ, a different portion of the disk is being observed. In the future, we plan to study the temperature differences across the disk by observing the system at $\psi \approx 0$ as a function of orbital phase.

b) *Emission Lines*

As shown in Figure 6, the N V and C IV line fluxes vary significantly as a function of phase. The general behavior of the lines strongly suggests that they are formed in or near the heated photosphere, as is the continuum, particularly N V, for which the equivalent width is roughly constant. The C IV flux does not vary as much, with the equivalent width increasing as one approaches eclipse. The high continuum flux exposures at $\phi = 0.8$–0.9 also have enhanced line emission. It is likely that the N V and C IV have a different origin from the visual emission lines which show no strong correlation with orbital phase (e.g., Crampton and Hutchings 1972; Barbon *et al.* 1974).

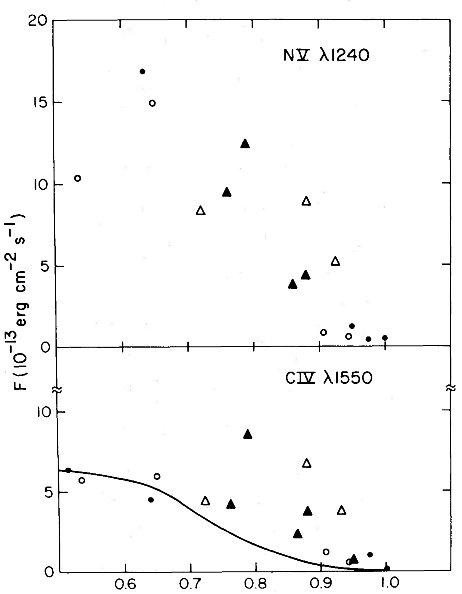

FIG. 6.—Variations with ϕ of emission-line fluxes for N V λ1240 and C IV λ1550.

A N V/C IV ratio greater than 1 is contrary to theoretical calculations of optically thin, X-ray heated gas (Hatchett, Buff, and McCray 1976). For a semi-infinite atmosphere, we may use their results to compute the C IV and N V luminosities, given $Lx = 1.5 \times 10^{37}$ $ergs^{-1}$ (Milgrom and Salpeter 1975) and the solid angle of X-rays intercepted by the primary star. Assuming the line flux is emitted into $\sim 2\pi$ steradians, the flux in N V is $\sim 9.5 \times 10^{-13}$ ergs cm^{-2} s^{-1} at the Earth, which is comparable to the maximum flux seen; however, the calculated flux for C IV is $\sim 5.8 \times 10^{-12}$ ergs cm^{-2} s^{-1}, 10 times the observed maximum; this result suggests the C IV is optically thick. The fact that the ratio of N V/C IV varies with phase suggests that excitation and optical depth effects may be important. Also it appears that the significant emission in these two lines is generated near the disk.

There is another possible contribution to the UV flux near eclipse. McCray and Lamb (1976) have suggested that an optically thick shell of gas accumulates at the magnetopause. The hard X-rays emitted closer to the neutron star heat the shell to $\sim 10^6$ K, and blackbody radiation from the shell accounts for an observed excess at 0.25 keV (Fritz *et al.* 1976; Catura and Acton 1975; Brunner 1978). Such emission would be negligible at $\phi = 0.5$, but could be detectable just before and after X-ray eclipse. Their maximum radius case (model 1) has half the 1300 Å flux as the $\phi = 0.5$, but could be detectable just before and after X-ray eclipse. Their maximum radius case (model 1) has half the 1300 Å flux as the $\phi = 0.095$, $\psi = 0.16$ spectrum; however, their smallest radius case (model 2) has an undetectable flux, so that we are unable to place serious constraints on the opaque shell model.

The data presented here are not sufficient to make unique distinctions between the disk model and other possible explanations of the excess light. Our data are concentrated on 35 day phases where the optical eclipse is significantly narrowed from the MS model calculations; one would expect an important disk contribution in all of the present UV data. We are therefore very limited in the tests possible on the basis of 35 day modulation. Also, the data indicate that the photosphere and the disk have similar radiation characteristics. In addition, the differences that have tentatively been attributed to a 35 day phase modulation difference might also be the result of a fluctuation in the heated photosphere or in a gas stream.

IV. CONCLUSIONS

The ultraviolet data verify in broad detail the general features of the model of HZ Her comprising a star whose photosphere is heated by the X-ray source, Her X-1, and a precessing accretion disk. Because of the small number of data points, we can only check for consistency with the enormously rich data set that is available in visible light. However, the UV provide unique insights into the physical conditions in this remarkable stellar system.

Specifically, we find the following: (*a*) Certain features in the light curve—excess emission near eclipse, broad shoulders near X-ray turnon, deficiency at maximum light—are consistent with the precessing disk model. (*b*) The continuum spectrum near maximum light cannot be fit to a single-temperature photosphere, but fits well to the MS model for an X-ray heated stellar surface. (*c*) The continuum spectrum near eclipse shows variations in shape that may be dependent on the aspect of the disk and should yield information regarding the disk's characteristics. Data taken near $\psi = 0$ are consistent in both temperature and size with the CGY disk model. (*d*) Neither the N V/C IV emission line strength or the continuum shape of the excess light in the system is consistent with the thermal emission of an optically thin, hot gas.

We have attempted to derive parameters for various parts of the system, and we hope to improve their accuracy with future observations since the present data indicate that, by appropriate choice of 35 day and orbital phases, clean separation can be obtained between the disk and photosphere components.

This work was the result of the pooling of observing time by US, British, and European investigators on *IUE* and was possible only through the close cooperation of the NASA and ESA project personnel. We also wish to thank the NASA resident astronomers, F. Espenak, A. Holm, F. Schiffer and C-C. Wu, for their assistance in obtaining the data and P. Perry for his assistance in reducing the data.

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