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FURTHER OPTICAL OBSERVATIONS OF HZ HERCULIS

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Optical observations of HZ Her made in the spring and summer of 1973 are presented. Some of the observations are practically coincident with estimated turn-on times for Her X-1 and others are simultaneous with X-ray observations made using the Copernicus satellite. Eight magnitudes were also measured from old plates for the epoch 1953-60; these measurements confirm the long-term variations for that epoch reported by Jones, Forman, and Liller (1973). An interesting theoretical explanation by Fabian, Pringle, and Rees (1973) for the persistence of large optical variations throughout the 35-day X-ray period is ruled out by simultaneous UHURU (X-ray) and Wise Observatory (optical) observations.

Key words: X-ray source — binary star — photometry

I. Introduction

The binary system consisting of HZ Herculis and Her X-1 has been the subject of many theoretical and observational investigations following the initial discovery that it contained a periodically pulsing X-ray source (Schreier et al. 1972), the suggestion by Liller (1972) that HZ Her was an interesting candidate for the optical source, and the positive identification by Bahcall and Bahcall (1972*a*). Some of the more-detailed optical observations are described by Bahcall and Bahcall (1972*b*), Davidsen et al. (1972), Forman, Jones, and Liller (1972), Bopp, Grupsmith, and Vanden Bout (1972), Crampton and Hutchings (1972), Groth and Nelson (1972), Lyutiy, Sunyaev, and Cherepashchuk, (1973), Petro and Hiltner (1973), Boynton et al. (1973), Bopp et al. (1973), Cocke et al. (1973), Chevalier and Ilovaisky (1973), Crampton (1974), Groth (1974).

We present in section II our new observational results (see Fig. 1) which include 76 *B* magnitudes measured during the spring and summer of 1973 at the Wise Observatory, as well as magnitudes measured on eight nights in the years 1953-60 with the University of Oklahoma astrographic telescope. Some theoretical inferences are presented in section III. Of special interest are our observations that are practically coincident with the estimated turn-on times for Her X-1 in 1973 May and August. We also report observations in 1973 August that were simultaneous with X-ray observations made using the Copernicus satellite (Triton 1973; Fabian and Hoffman 1973).

Our observations (see Table I) made during 1953 to 1960 confirm the long-term variations of that epoch reported by Jones, Forman, and Liller (1973). In agreement with their results we find that HZ Her was in a low-intensity state for the nights in 1953, 1954, and 1956 that are covered by our measurements. In addition, HZ Her was bright on the one night in 1960 covered by the observations.

II. Observations

A. *1973 Observing Season*

In Figure 1 we show the observed *B* magnitudes measured for 76 separate times during the period from 1973 March 1 to 1973 August 26. The results were obtained using the 1-meter Ritchey-Chrétien reflector telescope of the Wise Observatory with Kodak 103a-O plates exposed for 15 minutes behind a Wratten-47 filter. The magnitude system and the reduction procedure are the same as described by Bahcall and Bahcall (1972*b*); the typical rms error for an individual magnitude is 0^m1.

The turn-on times (UT dates) for the 35-day

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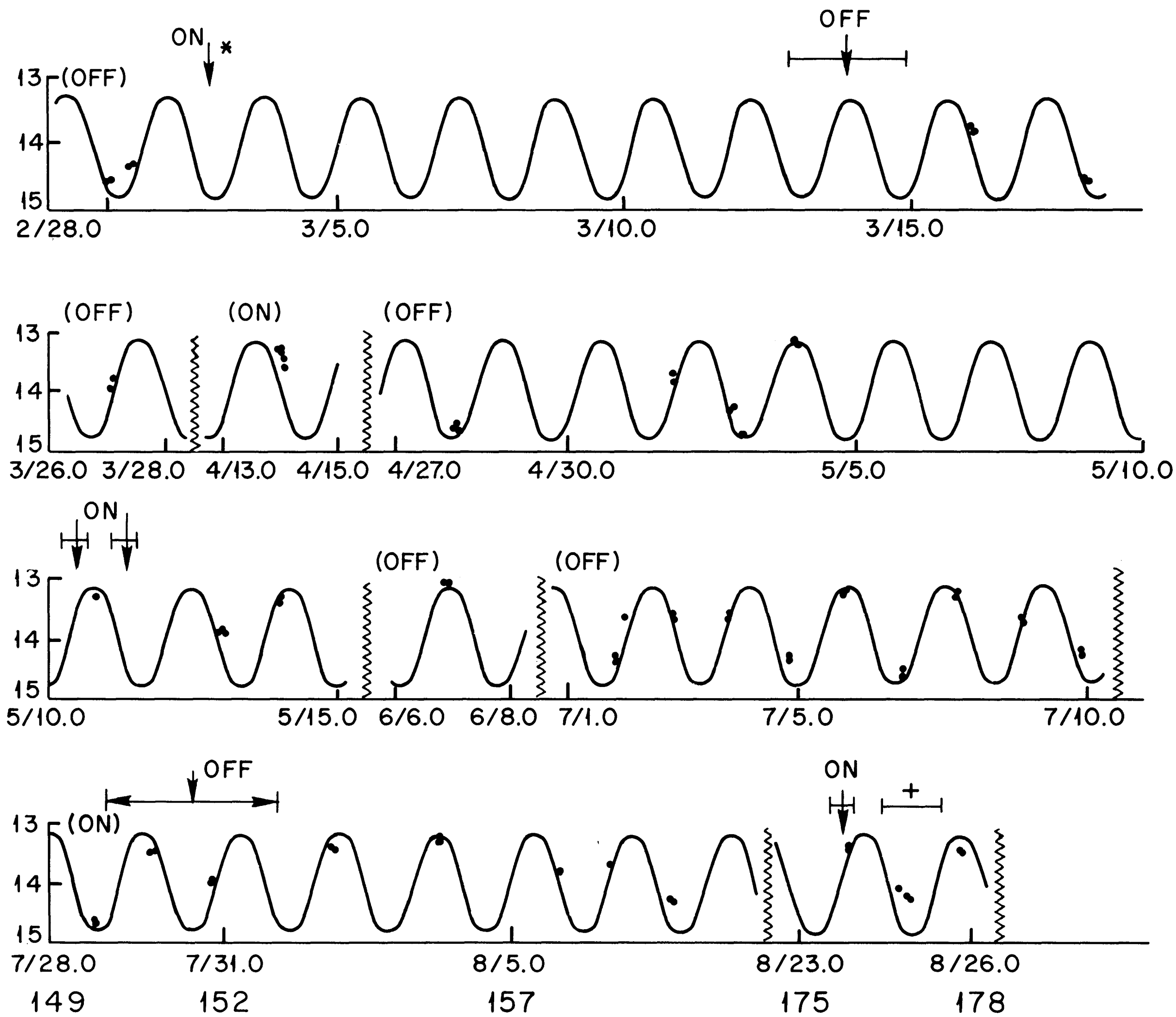

FIG. 1 — *B* magnitudes for 1973. The measured magnitudes are shown as black dots. During the period marked by † Her X-1 was observed to be "on" by the Copernicus satellite (Fabian and Hoffman 1973). The time marked by a * indicates that Her X-1 was observed to turn-on by the UHURU satellite (Tananbaum et al. 1973).

cycle of the X-ray source were calculated (cf. Groth 1974) using the observed turn-on times, 1973 March 1.72 ± 0.04 (see Tananbaum et al. 1973) and 1973 August 24.1 ± 1.04 (Tananbaum et al. 1973; Fabian and Hoffman 1973), plus the assumption (see Giacconi et al. 1973) that the turn-on times are quantized in units of approximately half the orbital period (i.e., the time between successive turn-ons is $(1.70[20 + n/2] \pm 0.2)$ days, $n = 0$, 1, or 2). These considerations uniquely fix the August turn-on time at August 23.8 ± 0.2 UT. The X-ray source gradually becomes unobservable (turn-off) 11 ± 1 days after each turn-on. Thus, the total uncertainty in the March turn-off is ± 1 day and the total uncertainty in the July/August turn-off time is ± 1.4 days (see Fig. 1). If the behavior of the 35-day cycle during the spring and summer of 1973 was the same as that suggested by the observations of Giacconi et al. (1973), then there are no additional uncertainties in the turn-on and turn-off times shown on Figure 1. (Of course, we cannot rule out the possibility of different behavior, e.g., the occurrence of values of n other than 0, 1, and 2.)

We note (see Fig. 1) that there are no very large departures from the previously determined (Bahcall and Bahcall 1972*b*) *average* light curve. HZ Her was in its variable state from 1973 March through August.

B. *Some Observations in 1953-60*

We give, in Table I, 18 individual magnitudes observed for HZ Her on eight separate nights during the years 1953 to 1960. The plates used (also Kodak 103a-O) were taken by B. Whitney with the 8.3-cm astrograph of the University of

TABLE I
Some Magnitudes of HZ Herculis 1950-1960

Plate No.	Year	Julian Date 2,400,000+	Phase	m_B	Remarks
R 7558	1953	(24) 34595.69	0.29	14.6	
R 7638	1953	34632.58	0.98	(14.6)	estimated
R 8022	1954	34829.81	0.99	14.54	
R 8023	1954	34829.83	0.00	14.54	
R 8207	1954	34925.70	0.39	14.95	
R 8208	1954	34925.72	0.40	14.43	
R 8934	1955	35392.59	0.00	(14.7)	estimated
R 8935	1955	35392.60	0.01	14.5	
R 8936	1955	35392.61	0.02	14.7	
R 8937	1955	35392.63	0.025	(14.7)	estimated
R 9309	1956	35605.755	0.38	14.7	
R 9310	1956	35605.77	0.39	14.8	
R 9311	1956	35605.78	0.40	14.6	
R 9438	1956	35698.73	0.07	14.4	
R 9439	1956	35698.74	0.076	(14.6)	faint image
R 9440	1956	35698.75	0.082	14.5	
R 11690	1960	37115.65	0.46	13.37	
R 11691	1960	37115.66	0.47	(13.0)	extrapolated

Oklahoma and were reduced by one of us (T.J.H.) according to the magnitude system of Bahcall and Bahcall (1972*b*).

C. *Position*

The position of HZ Her has been measured with the Mann x-y comparator of Tel Aviv University on an epoch 1972 plate (no. MR-692) taken at Wise Observatory. Using a series of reference stars and the standard reduction procedure of Véron and Véron (1973), we find the position of HZ Her to be

$$\alpha(1950) = 16^{h}56^{m}01^{s}.67, \delta(1950) = +35°25'05''.1$$

with a probable error of 0''.3 in either coordinate.

III. Discussion

A. *Phase Lag and Asymmetry*

The $1^{d}.7$ periodicities of the X-ray and optical light curves are equal to high accuracy (see especially Jones et al. 1973); they result from the orbital period, P, of the binary system. The numerical value of P is known very accurately from the X-ray observations (Tananbaum et al. 1972; Giacconi et al. 1973). It has also been shown that the optical light curve is fitted remarkably well by a simple law of the form $L_B = L_0(1 - A \cos 2\pi\phi)$, where L_B is the intensity in the B-band, ϕ is the X-ray orbital phase, and L_0 and A are constants (Bahcall and Bahcall 1972*b*; Bahcall, Joss, and Avni 1974). We have combined the 1973 data with the Wise Observatory data of 1972 (Bahcall and Bahcall (1972*b*) plus a few additional data of 1972 September) to set an improved limit on a possible phase lag between optical and X-ray light curves (cf. Bahcall et al. 1974); this limit constitutes a valuable constraint on theoretical models.

We define the phase lag, δ, by the light curve $L_B = L_0[1 - A \cos 2\pi(\phi - \delta/P)]$, which is symmetric in shape [i.e., $L_B(\phi - \delta/P) = L_B(-[\phi - \delta/P])$]. Fitting our total of 159 data points to a light curve of this form, we find that $A = 0.57 \pm 0.02$ and $\delta = 0.003 \pm 0.010$ day (approximate single parameter 95% confidence limits). Thus, $|\delta| \lesssim 0.01$ day = 15 minutes.

If we allow for a possible *asymmetry* in the light curve [i.e., $L_B(\phi - \delta/P) \neq L_B(-[\phi - \delta/P])$], the limit on the phase lag becomes less precise. For example, when we fit our data to light curves of the form.

$$L_B = L_0[1 - A_1 \cos 2\pi(\phi - \delta_1/P) + B_1 \sin 4\pi\phi]$$

or

$$L_B = L_0[1 - A_2 \cos 2\pi(\phi - \delta_2/P) + B_2 \sin 4\pi(\phi - \delta_2/P)] \quad ,$$

we obtain, respectively,

$$A_1 = 0.57 \pm 0.02, B_1 = 0.023 \pm 0.029, \delta_1 = 0.011 \pm 0.014 \text{ day} \quad ,$$

and

$$A_2 = 0.57 \pm 0.02, B_2 = 0.016 \pm 0.013, \delta_2 = 0.035 \pm 0.028 \text{ day} \quad .$$

(For the present data, additional terms in the Fourier-series expansion of L_B are generally consistent with zero.) Thus, there is some marginal evidence for an asymmetry and for the suggestion that the optical minimum (or maximum) follows the X-ray minimum (or maximum). However, both these marginal suggestions are dependent upon estimates of errors made with an average light curve that has no 35-day dependence included; more precise photometric data (now available from several groups) should be used to test for small asymmetries and phase lags.

B. *"On" and "Off" States*

Finally we note that the original observations at Wise Observatory can rule out an interesting theoretical suggestion recently made by Fabian, Pringle, and Rees (1973). These authors propose that the apparent absence of a very large 35-day effect in the optical light curve may be explained by assuming that the X-ray source was really "on" at UHURU energies whenever the optical observations were being made. They note that the published UHURU observations made after the optical identification of HZ Her were always performed during "on" periods. However, UHURU observations were also made prior to turn-on times in order to determine the onset times accurately. Schreier (1974) has kindly informed us that UHURU detected no measurable X-ray emission from Her X-1 on 1972 August 4.97, 5.25, 5.35, 5.95, and 6.03 (UT dates) prior to the

X-ray turn-on at August 6.99. Bahcall and Bahcall (1972*b*) (see their Fig. 1) report seven observations each night of HZ Her from 1972 August 4.78 to 4.92 and on 1972 August 5.76 to 5.94. On both nights, the light curve of HZ Her was normal, contrary to the suggestion of Fabian et al. (1973).

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