IDENTIFICATION OF THE X-RAY PULSAR IN HERCULES: A NEW OPTICAL PULSAR

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ABSTRACT

A series of photographic, photoelectric, and spectroscopic observations beginning 1972 June 1 has led to the optical identification of Her X-1 (2U 1705 + 34), a pulsed X-ray source in an eclipsing binary system, with the thirteenth magnitude blue variable star HZ Herculis. The detection of optical pulses at the frequency of the X-ray pulsar on three nights makes the identification conclusive and establishes HZ Her as the second known optical pulsar. The strength of the optical pulses may be correlated with the orbital phase but is not obviously related to the high or low intensity states of the X-ray source.

I. INTRODUCTION

The remarkable discovery by Uhuru (Schreier et al. 1972, Tananbaum et al. 1972) of a class of eclipsing binary systems containing pulsed X-ray sources promises to yield a wealth of new information on stellar evolution. We present here a report of our successful search for the optical counterpart of one of these objects, Her X-1 (2U 1705 + 34). The thirteenth magnitude blue variable star HZ Herculis, which lies near the center of the latest error box of the X-ray source (Clark et al. 1972) shows 1.8 magnitude variations in B consistent with the 1.70017 day orbital period of the X-ray source. Minimum light occurs close to the center of the X-ray eclipse. More conclusively, we have detected optical pulses from HZ Her with a period of 1.2379 ± 0.0002 seconds, which is identical with the period of the X-ray pulsar. The power in the optical pulses varies, and appears to be correlated with orbital phase. A maximum pulsed fraction of 0.2% was observed on 1972 August 6. A tentative detection of optical pulses from

HZ Her has been reported previously by Lamb and Sorvari (1972). Spectra obtained with the 120-inch telescope at Lick Observatory show strong Balmer and He I absorption lines suggesting a B type spectrum. The light curve, pulsations, and spectra are discussed separately in the following sections.

II. PHOTOMETRIC OBSERVATIONS

Following the revision of the location error box of Her X-1 (Clark et al. 1972) we began a search for an optical identification of the source. Plates were obtained with the 30-inch (76-cm) telescope of the Leuschner Observatory of the University of California, Berkeley, beginning 1972 June 1. Exposures on Kodak 103 aO emulsions with Schott GG-13 and UG-2 filters revealed a thirteenth magnitude star with a substantial ultraviolet excess, which was immediately identified with the catalogued variable star HZ Her (Kukarkin et al. 1969). Variability was first reported by Hoffmeister (1941), who noted that HZ Her was bluer than neighboring stars and concluded it was an irregular variable of the RW Aurigae type.

Photographic and photoelectric observations were undertaken in June and July to detect an effect which might be related to the turn-on or turn-off of the X-ray source, which was reported to have a 36-day period (Tananbaum et al. 1972). A series of good photoelectric observations on three successive nights was finally obtained between 13 and 15 July, and marked variability in times as short as ten minutes was observed. On July 14 the B magnitude of HZ Her declined steadily, the total change observed in five hours amounting to 0.9 magnitudes. On the other two nights its behavior was more erratic, showing flare-ups of 0.2 to 0.3 magnitudes in a few minutes, superposed on a generally rising light level.

Bahcall and Bahcall (1972) and Liller (1972) have reported that HZ Her varies with the 1.7 day eclipse cycle of Her X-1. Although our observations are not sufficient to establish the periodic behavior, they are consistent with that result. The light curve obtained by assuming a 1.70017 day period is shown in Figure 1, which includes photographic and photoelectric measurements made on 12 nights in June, July, and August.

A schematic representation of the X-ray light curve is shown for comparison. The most remarkable contrast is the broadness of the optical minimum which begins at least 0.2 in phase before the X-ray eclipse. The total variation of B is 1.8 magnitude, while the X-ray minimum is at least a factor of 20 below the high intensity level (Tananbaum, 1972).

Several photoelectric measurements of U were also obtained, and the variation of (U-B) with phase is also displayed in Figure 1. At maximum light (U-B) ≈ -0.7 while at minimum (U-B) $\approx +0.3$. Reliable measurements of V were not obtained because of the sky brightness at Leuschner.

III. OBSERVATIONS OF OPTICAL PULSES

We have searched for optical pulses from HZ Her on ten nights in July and August, 1972, with an EMI 9658 photomultiplier tube mounted at the focus of the 24-inch (61 cm) telescope at Lick Observatory. The photopulses were converted to logic pulses by an amplifier discriminator and then used for synchronous signal-averaging with the electronics described previously by Nelson et al. (1970). In parallel with the signal-averaging the pulses were integrated for 10 ms and passed through a divider, subtractor, tape interface, Kennedy 1600 incremental tape recorder and onto a seven track digital tape for later Fourier analysis. A General Radio 1120 frequency counter which displayed the photon counting rate was used to assist in the offset guiding and monitoring of HZ Her. Typical counting rates were 5000 counts/sec in the high state and 2000 counts/sec in eclipse of which 900 counts/sec were from the sky.

The major analysis in the pulsation detection experiment is an efficient version of the Cooley-Tukey Fourier transform which has been calibrated previously on the Crab Pulsar on 1971 April 22, October 13, and 1972 February 28, and August 11 by simultaneous synchronous signal averaging for run lengths of $2^{18} \times 4$ ms, $2^{20} \times 4$ ms, $2^{21} \times 1$ ms, and $2^{16} \times 10$ ms respectively. By a summation of harmonics of the 100 to 150 most significant spikes the transform recovered at least 85% of the signal/noise ratio obtained from signal averaging.

For additional accurate calibration, a Monte-Carlo program generated a run with 50 counts/sec underneath a 30 Hz sine-wave form and an 8000 count/sec background for a run of $2^{18} \times 4$ ms which produced a peak of 11 to 12 σ in the transform. The pulsation levels given in Figure 2 were derived from the Monte Carlo simulation and from the fact that the percentage of pulsation with respect to a reference light level varies inversely as the strength of that light level and as the square root of the ratio of the length of run to background counting rate. Transform lengths of 2^{18} -2^{20} $\times$ 10 ms were typical in the reduction of the data. A reference level of 4000 counts/sec was chosen because this represents both HZ Her at its brightest phase and the mean light level seen from the star plus sky in the 17" diaphragm used.

Coherent optical pulsations, lasting from 45 to 90 minutes were detected on the nights of August 4, 6, and 11 with confidence levels of 7σ, 5σ, and 5σ respectively. The nights of July 21, 22, 28, and August 3, 5, and 8 gave negative results down to less than 2σ. A marginal result of 2.5σ was obtained on the night of August 7. The data are plotted versus orbital phase in Figure 2.

The August 4 pulsations occurred during the second half of three hours of observations and clearly showed the fundamental and first two higher harmonics. The power in the three frequencies decreased somewhat in the second 45 minute interval after the appearance of pulsations, when the orbital phase of Her X-1 passed from the 0.10 to 0.12 range to the 0.12 to 0.14 range. The apparent frequencies of 0.8079 and 0.8083 ± 0.0002 Hz from the two 45-minute data sections were both consistent with the progression of doppler shift of the Her X-1 pulsar according to the ephemeris published by Tananbaum et al. (1972). The ratio of power in the three frequencies was roughly 7:2:3.

The August 6 pulsations occurred mostly in the first hour of a three-hour observation (when the Her X-1 orbital phase was 0.24 to 0.26) and have only slight power beyond the fundamental frequency. The intensity of pulsation during this period was uniform, but the pulsation frequency was measured to be lower than the expected doppler-shifted frequency of 0.8083 Hz with the power falling in the frequency bin corresponding to the zero-velocity average of 0.8079 ± 0.0002 Hz for the binary system. We know of no instrumental effect which could account for this frequency difference. Five nights later, with the binary again near the same phase (0.18 to 0.22) pulsations were detected for a 90 minute period with the predicted doppler-shifted frequency of 0.8083 ± 0.0002 Hz. Three transforms in the first half, middle, and second half of this period indicate that the intensity varied from high to low, and then to high again. The three hours following this period (phase 0.22 to 0.29) showed no evidence of pulsations.

The marginal result of August 7 occurred during the second quarter of a three hour observation and may have been diminished by bad weather. The binary phase was 0.87 and the pulsation frequency of 0.8075 ±0.0002 Hz agrees well with the doppler shift expected for Her X-1.

The complex phases obtained from the sub-sections of data for all three nights with substantial power show that the source of the pulsations is coherent.

IV. SPECTROSCOPIC OBSERVATIONS

Spectra of HZ Her were obtained on 1972 June 15 and August 5, 6, and 7 when the phases of Her X-1 were 0.70, 0.65, 0.23, and 0.82, respectively. The observations were made using the Lick Observatory 120 inch (305 cm) telescope and the Image-Dissector Scanner (IDS) (Wampler and Robinson, 1972). Eight minute integrations were usually sufficient to yield more than 2000 counts per channel across most of the 2000 Å interval scanned. Three of the spectra were centered at 5700 Å and the remaining one was centered at 7100 Å. Spectra were not obtained in the blue because of the requirements of concurrent research with the IDS.

All the spectra are qualitatively similar. Each shows absorption at Hβ, HeI λλ4922, 5016, 5876, 6678, and Hα. Figure 3 shows a representative observation. The shape of the continuum is artificial, and is created by a quartz lamp used as a normalization to remove the instrumental response. No trace of emission has been found on any of the spectra. The observation of 7 August, obtained only three hours after the X-ray source made a transition from low to high intensity states (Tananbaum, 1972), is of lower quality than the others due to poor weather. However, it shows no significant differences from the previous spectra obtained under good conditions.

On the basis of the helium line strengths, we tentatively classify HZ Her as an early B star, at least during the phases at which we have observed it. The equivalent width of HeI λ4922 is approximately 1.0 Å which implies HZ Her is near the HeI maximum at B2. We obtain equivalent widths of 9.5 Å and 5.5 Å for Hβ and Hα, respectively. More precise classification is not possible at present because the IDS has not yet been used to observe large numbers of standard stars.

Although the ability of the IDS to measure stellar radial velocities is as yet untested, we see no convincing evidence for large velocities as suggested by Bopp et al. (1972). All of our spectra give essentially zero radial velocity with a maximum error of ±100 km/sec. If large radial velocities are sometimes observed, it is probably due to gas streaming in this close binary system.

V. SUMMARY

To summarize our principal observations we find:

1. HZ Her sometimes emits optical pulses at the frequency of the X-ray pulsar Her X-1. In the best case about 0.2% of the maximum light from this system appears in these pulses. The pulses were detected during both high and low intensity states of the X-ray source. Our three strongest detections of optical pulses occurred between 0.1 and 0.3 in orbital phase. We also note that the observations of Lamb and Sorvari (1972) and the negative results of Crampton and Morbey (1972) are consistent with this possible correlation between pulsations and phase.

2. The light curve of HZ Her is consistent with the 1.70017 day eclipse period of the X-ray source. Minimum light coincides with the X-ray eclipse, but the transition from maximum to minimum takes much longer in the optical region.

3. Flares of 0.2 to 0.3 magnitudes in times shorter than an hour are superposed on the periodic variation.

4. The ultraviolet excess of HZ Her is greatest at maximum light. The total variation of U-B is ~1.0 magnitude.

5. The spectrum appears to be early type B, at least near phases 0.25 and 0.75. No emission lines have been observed. A spectrum obtained shortly after the X-ray source turned-on showed no differences from those obtained earlier.

The correlated optical and X-ray variations at 1.2378 seconds and 1.70017 days establish the identity of HZ Her and Her X-1 conclusively. With the exception of the Crab pulsar and several supernova remnants, this is the first absolutely certain identification of a galactic X-ray source.

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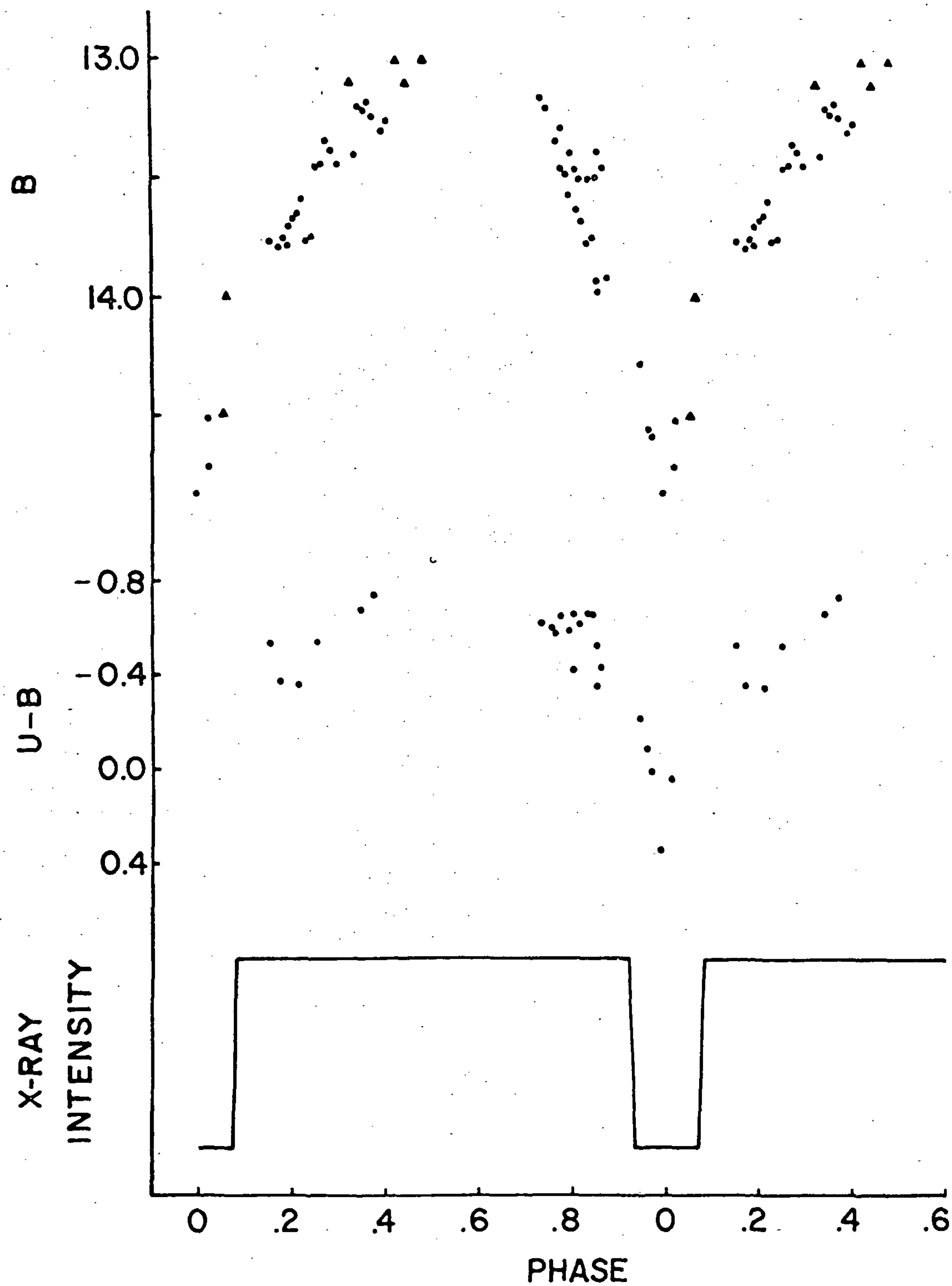

Figure 1
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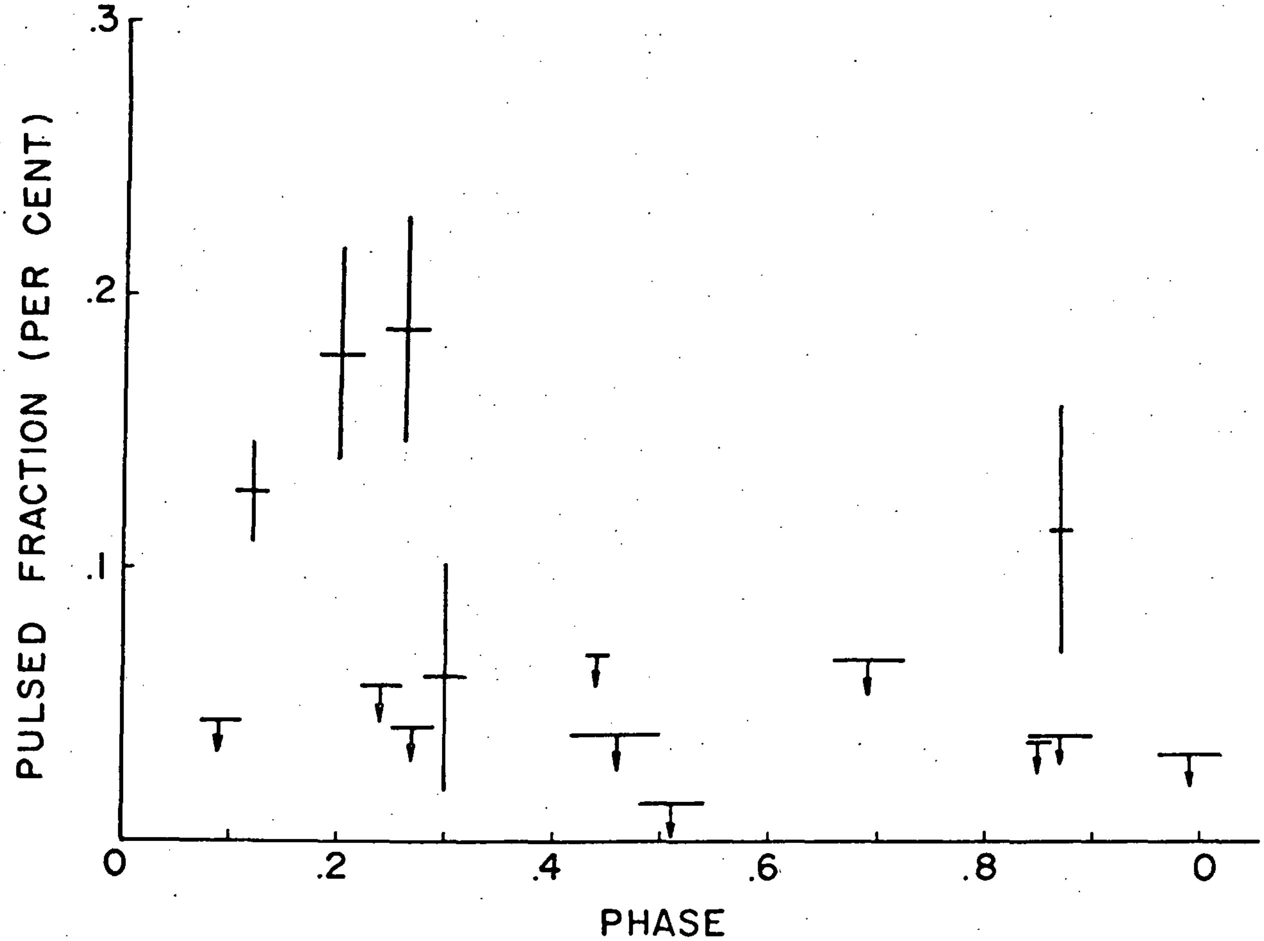

Figure 2
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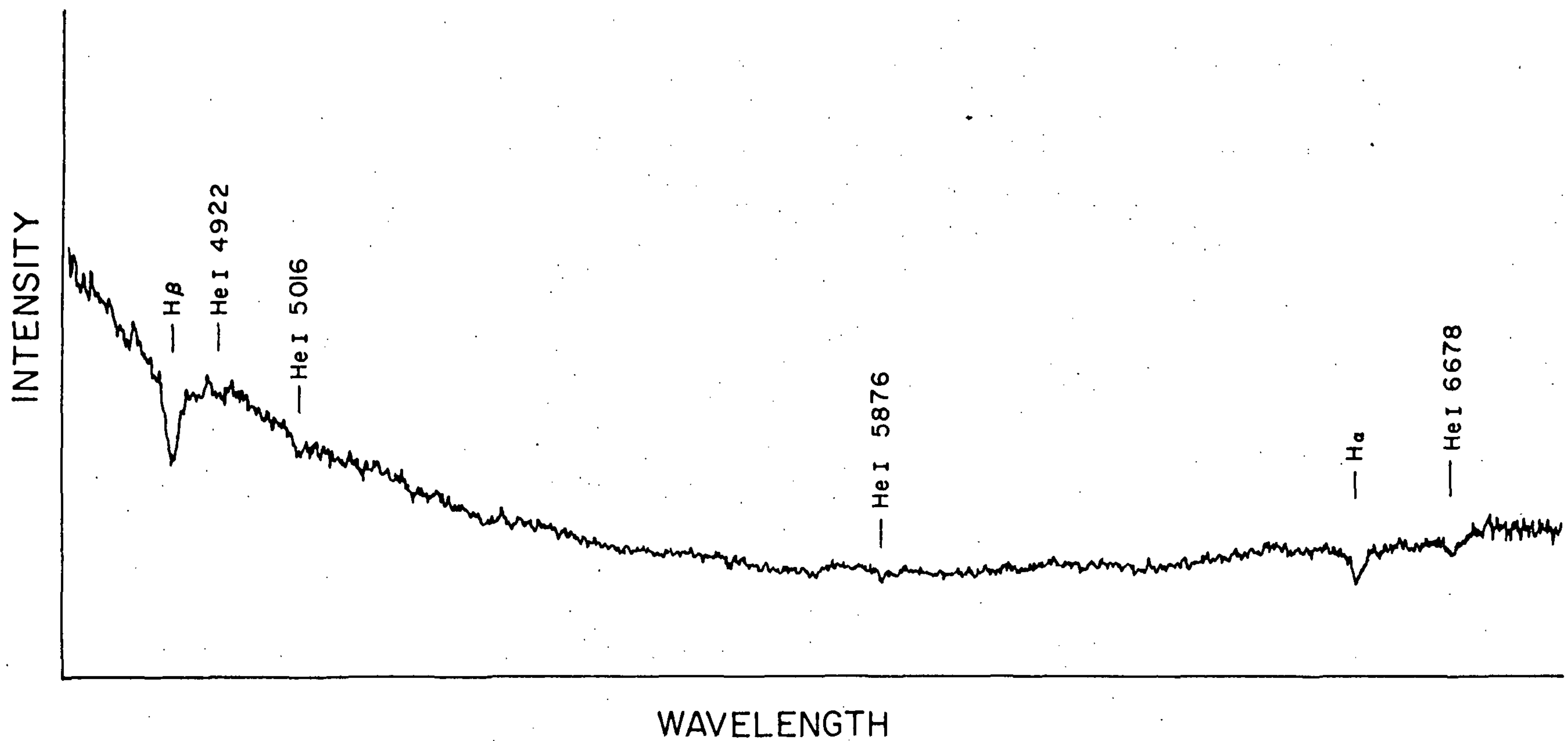

Figure 3
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FIGURE CAPTIONS

Fig. 1 Light curve of HZ Her for P = 1.70017 days, T_o = J.D. 2441329.5772. B magnitude is displayed in the upper portion, (U-B) in the center, and the X-ray variation at the bottom. Phase 0.0 corresponds to the center of the X-ray eclipse. Mean errors are 0.05 in B and 0.07 in U-B. ▲ photographic observations, ● photoelectric observations.

Fig. 2 Pulsed fraction of the maximum light from HZ Her vs. phase. Error bars and upper limits are $\pm 1\ \sigma$. Positive detections were obtained on three different nights.

Fig. 3 Spectrum of HZ Her obtained with the Lick 120-inch telescope and Image Dissector Scanner on 1972 August 6 at 0430 UT. The shape of the continuum reflects that of a quartz lamp used for normalization.