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X-RAY PULSE PROFILE AND CELESTIAL POSITION OF HERCULES X-1*

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ABSTRACT

The celestial position of the binary X-ray source Her X-1 has been measured with a precision of 30″ and, within the uncertainties, agrees with the position of the optical variable HZ Herculis. An average light curve for the 1.24-s periodicity has been obtained with ~10 ms resolution. The average pulse is a double-peaked structure which shows significant intensity changes in time scales down to 30 ms.

Subject headings: binaries — pulsars — X-ray sources

The 1.7^d eclipsing binary X-ray source Her X-1 pulses every 1.24 s and also exhibits at 35^d periodicity (Tananbaum *et al.* 1972). A relatively precise X-ray location ($\sim 0\overset{\circ}{.}3$) by Clark *et al.* (1972) led to the discovery of an optical 1.7^d period in HZ Herculis (Liller 1972; Bahcall and Bahcall 1972; Forman, Jones, and Liller 1972; Davidson *et al.* 1972). The precise measurement of the celestial position of Her X-1 reported here confirms this identification. The 1.24-s pulse profile given here bears directly upon theoretical models for the X-ray generation process.

Our observations were made from an Aerobee 170 sounding rocket launched from White Sands Missile Range at 0300 hours, 1972 September 16 (UT). At this time, the source was about midway through the 9-day "on" portion of its 35^d cycle and at phase 0.308 in its 1.7^d period (phase 0.0 = center of eclipse). The entire flight was devoted to a 260-s observation of Her X-1. The payload instrumentation consisted of (1) a rotating modulation collimator system for the position measurement (Mertz 1967; Schnopper *et al.* 1970; Rappaport, Zaumen, and Doxsey 1971), having a characteristic angle of $2\overset{'}{.}1$ FWHM, a field of view of $16° \times 16°$ FWHM, and a peak effective area of ~ 100 cm^2, and (2) a bank of four counters, totaling ~ 600 cm^2, with $\sim 16° \times 16°$ FWHM collimation for the pulse profile measurement.

The position analysis yielded only one source which clearly stood above the background (i.e., $\sim 6\ \sigma$) in the entire $10° \times 10°$ field we searched. The most probable position for the source is 5″ from HZ Herculis. The error circle (90 percent confidence) has a radius of $\sim 30''$ (fig. 1 [plate L3]).

The pulse-profile observations yielded about 103,000 counts including background, each detected with a time resolution of 1 ms. The calculated power density spectrum shows six harmonics in addition to the primary frequency of 0.8083 ± 0.0002 Hz. This agrees with the frequency calculated from the heliocentric period (Giacconi *et al.* 1973). No other periodicities are present at a significant level, i.e., about 10 percent ($3\ \sigma$) of the Her X-1 signal. An autocorrelation analysis shows no aperiodic variations

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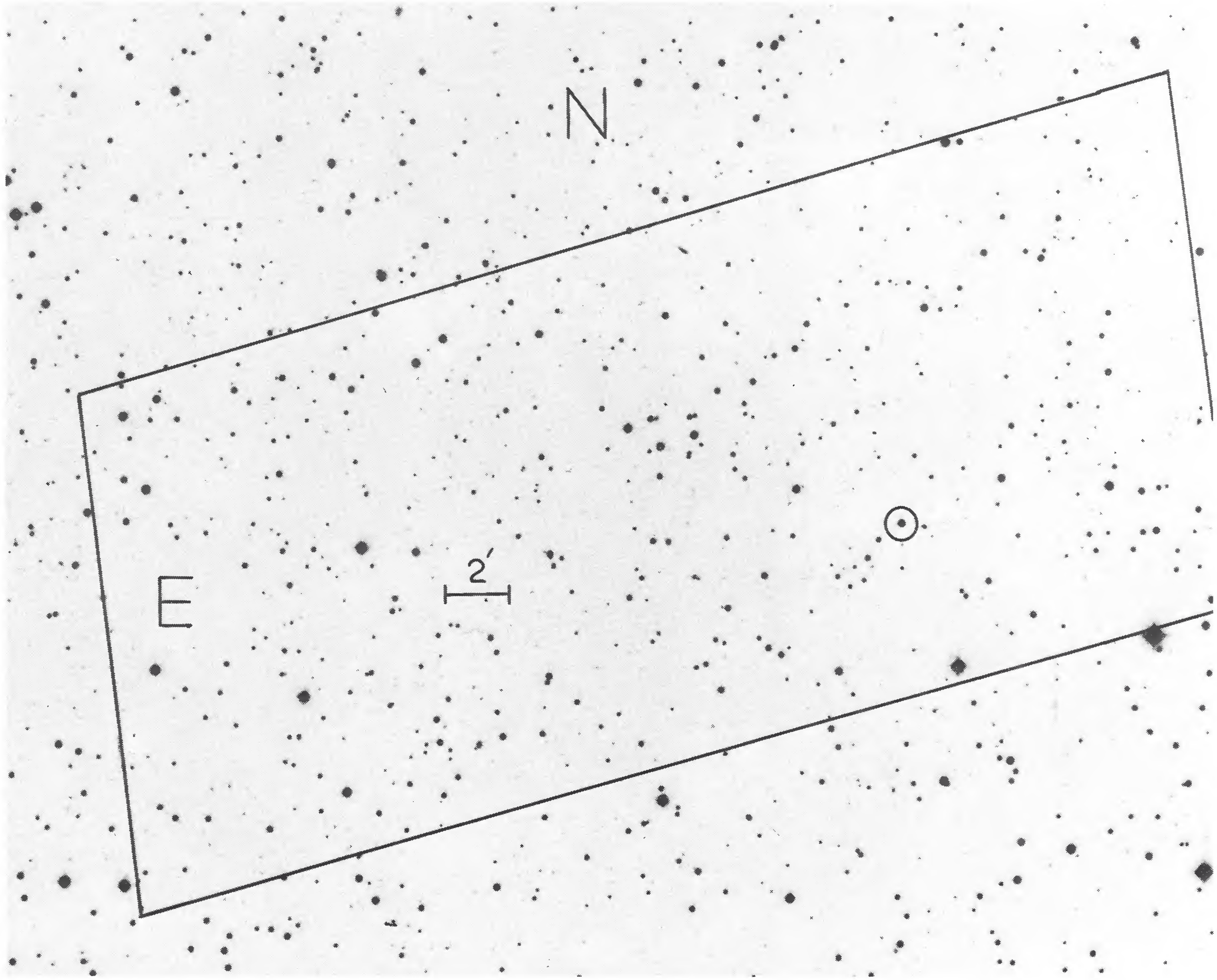

FIG. 1.—Enlargement of a blue *Palomar Sky Survey* print (© National Geographic Society) of the Her X-1 region. The 30″ radius circle denotes the region of uncertainty (90 percent confidence) in the present X-ray measurement. The parallelogram is the earlier X-ray error box as derived (Doxsey *et al.* 1972) from OSO-7 and *Uhuru* results. The relatively bright star within 5″ of the circle center is HZ Her: $\alpha(1950) = 16^h56^m02^s$, $\delta(1950) = 35°25'.1$.

DOXSEY *et al.* (*see* page L25).

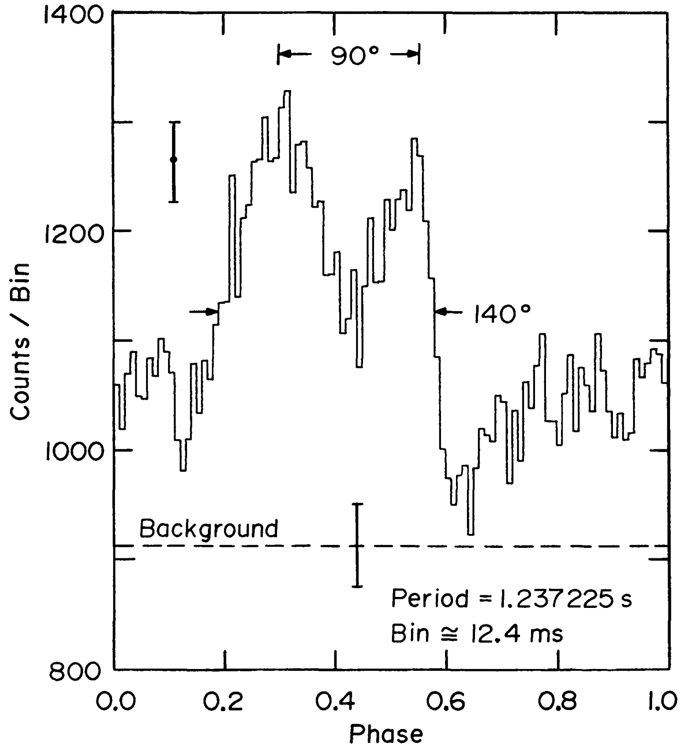

FIG. 2.—Counting rates from Her X-1, superposed modulo the pulse period, for the entire data train (260 s). The rates have been corrected for a dead time of ~6 percent. The background level was obtained from rates measured during two earlier flights of the same payload; the corresponding error bar indicates the estimated uncertainty.

of intensity on time scales from 1 s to about 1 ms, with intensities greater than ~20 percent (3 σ) of Her X-1.

The data were folded modulo the apparent pulse period of 1.237225 s (fig. 2). The average pulse profile shows a double-peaked main pulse. The two peaks have the same maximum intensity, but markedly different widths. The trailing edge of the second peak falls very quickly, in 30–40 ms, with a minimum immediately following. About 60 percent of the source counts occur during the major double pulse, i.e., during ~140° of phase.

The energy dependence of the pulse profile was investigated by dividing the data into two energy channels (fig. 3*a*). The heights of the two peaks of the pulse are about equal in the low-energy channel. At higher energies, the first peak is apparently more intense (95 percent confidence). The data were also divided into four consecutive 65-s intervals (fig. 3*b*). The χ^2 probability was calculated between pairs of intervals. The variation between the first and fourth was the greatest (χ^2 probability $= 0.98$). The probability for this deviation to occur in any one of the comparisons is ~10 percent.

Accretion of matter at the magnetic poles of a neutron star could lead to isotropic X-ray emission, which would be modified by electron scattering in the infalling plasma above the poles (Pringle and Rees 1972; Lamb, Pethick, and Pines 1972). This would reduce the intensity along the magnetic axis relative to the intensity perpendicular to the axis, yielding an emission pattern which peaks at the magnetic equator and goes to a minimum at the poles. If the magnetic axis is not aligned with the spin axis, the signal at the Earth will vary as the emission pattern is swept around the sky. The pulse profile at the Earth will be a function of the angles defined in

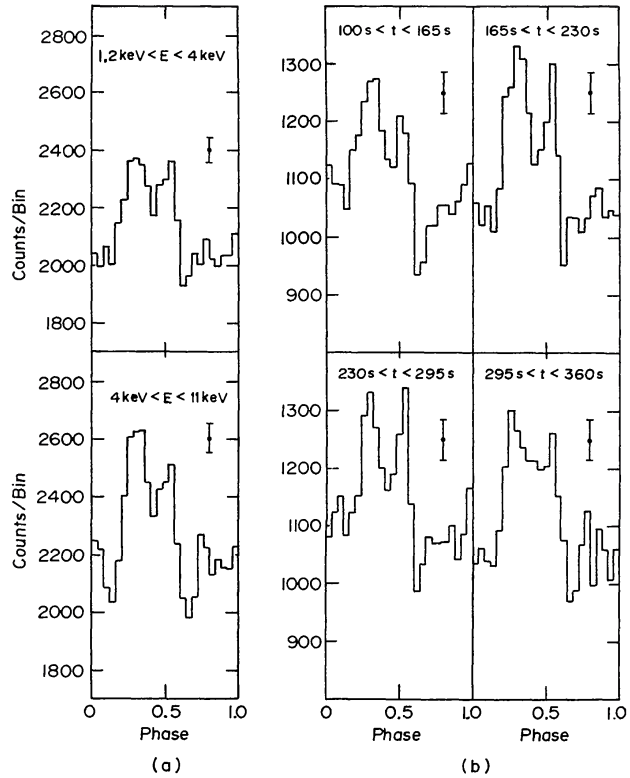

FIG. 3.—Counting rates from Her X-1, superposed modulo the pulse period for two different energy intervals over the entire flight (fig. 3*a*), and for four successive 65-s intervals over the entire energy range (fig. 3*b*). The rates have been corrected for dead times averaging 20 percent in (*a*) and 6 percent in (*b*).

figure 4 and the exact shape of the emission pattern. We have carried out simulations under the assumption that the emission from both poles is identical and of the form

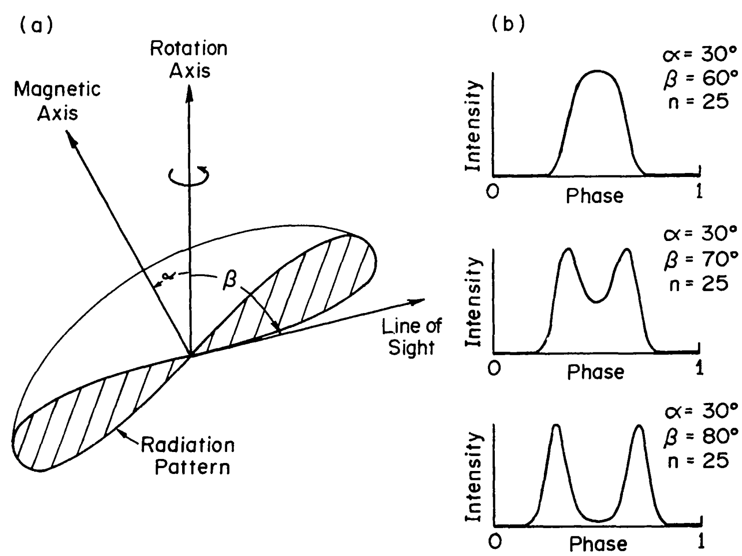

FIG. 4.—Radiation pattern and simulated pulse shapes for a simple accretion model (see text). The intermediate case ($\beta = 70°$) closely resembles the major features of the observed pulse shape.

$I(\theta) \propto \sin^n \theta$, where θ is the polar angle from the magnetic axis. A double-peaked pulse with overall width and peak separation similar to that seen in our data can be produced (fig. 4) for several choices of the angles involved, and for an emission pattern with FWHM $\sim 25°$ (i.e., $n \approx 25$). This simple model does not explain the asymmetry and the energy dependence of the profile. Both effects require an azimuthal variation in the emission pattern which might arise from the rotation of the object. Also, this model does not explain the emission after phase 0.7 when the line of sight is closest to the magnetic axis and the emission should be at a minimum.

The pulse profile which we have observed was taken at one specific point in the 35^d and 1.7^d cycles. Variations in the emission pattern or precession of the spin axis could lead to variations of the pulse profile.

The present rocket flight was conducted immediately following a real-time measurement of the source intensity by the *Uhuru* satellite. We thank the AS&E group, the staffs of the SAS Mission Control Center, the Sounding Rocket Branch at Goddard Space Flight Center, and the White Sands Missile Range for their support in this coordinated operation. We also thank Messrs. E. Boughan, W. Cash, G. Moore, and F. Primini of MIT for their support in the launch and the data analysis.

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