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ABSTRACT

Optical pulsations from HZ Her have now been detected on about 10 nights out of 22. These pulsations are weak ($< .2\%$), variable in intensity and duty cycle, and occur near the Her X-1 pulsar frequency. Because of the unexpected variability of the results, a detailed discussion is presented.

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I. INTRODUCTION

In 1972 the Uhuru satellite discovered an X-ray pulsar with a frequency of .80787 Hz in a binary system with a period of 1.70017 days. (Tananbaum et al. 1972). In addition to the 1.7 day period, a 36 day cycle of X-ray activity was noticed with X-rays present for 10-11 days, and absent for 26 days. Later in 1972, an optical counterpart was found – a binary system with the same 1.7 day period – thus confirming that the optical system (HZ Her) and the X-ray system (Her X-1) are one and the same (Bahcall and Bahcall, Liller, Davidsen et al. 1972). Following this discovery, much effort has been devoted to the study of the optical properties of HZ Her, both on a long time scale (Davidsen et al., Forman et al., Bahcall and Bahcall 1972) and on a short time scale, looking for optical pulsation (Lamb and Sorvari, Davidsen et al., Groth and Nelson 1972).

The detection of optical pulsations was first reported by Lamb and Sorvari (1972) and more recently by a group at Berkeley (Davidsen et al. 1972) who claimed to see intermittant pulsation at the .2% level. This paper discusses these and further optical pulsation data taken at Lick Observatory between July 1972 and January 1973.

II. EXPERIMENTAL PROCEDURE AND ANALYSIS

The data were taken at the 61 cm telescope at Lick Observatory, using an unfiltered EMI 9658A phototube with a high quantum efficiency broad band (S-20) photocathode. The signal was digitized and then the number of photons in consecutive 10 (or 40) millisecond time intervals was recorded on digital tape. Typical runs contained up to one million such time intervals covering about 3 continuous hours on the star. Because each word on the tape contains only 6 bits, the number of photons was divided by a specified integer, and an appropriate constant was subtracted from this quotient such that the mean word content was about 32. Typical count rates from the star alone varied from 1000 to 4000 counts/sec, depending on the binary phase.

The data tapes were then read into a CDC 6600 computer where the data were analyzed using the Cooley-Tukey fast Fourier transform algorithm. Fourier transforms up to 2^{21} (~ 2 million) words have been performed on this computer. The power spectrum was obtained by squaring the complex Fourier coefficients. This power spectrum was normalized so that the local mean power level was 1 unit; this normalization would in principle be independent of frequency for a flat spectrum resulting from "white" noise. However, because the low end of the spectrum ($\leq$ .25 Hz) is subject to additional noise from fluctuations in the "seeing" and from telescope vibration, in practice the normalization varied with frequency and was defined by the local average of the power spectrum (typically .001 of the total frequency interval). The low frequency end of a typical un-normalized spectrum is shown in Fig. 1. The flat contribution to the power spectrum results from statistical fluctuations in the observed light level. A slight slope can still be seen by comparing the low and high frequency regions in Fig. 1. Any purely sinusoidal fluctuation in the observed object would of course add power only to a single frequency bin.

The fluctuations in the power level of a given frequency bin are not distributed according to Gaussian statistics, but rather are distributed exponentially:

$$\text{Prob}\ (x)\ dx = e^{-x} dx, \quad x = \text{power in bin/local mean power.}$$

An example is shown in Fig. 2 which displays the distribution of normalized power in Run 17, where the clearest pulsar signal is found. The solid line represents the theoretical expectation for this distribution exclusive of any real signals. This beautiful agreement confirms the validity of the exponential probability distribution. The periodic signal from HZ Her shows up in the bin farthest to the right.

The region of the power spectrum for Run 17 near the frequency of Her X-1 is shown in Fig. 3. The signal indicated in Fig. 2 shows quite clearly in this figure. Statistical fluctuations would cause this much power in <u>any</u> bin in a transform only once in 100,000 such transforms. The probability of seeing this much power in a <u>specified</u> bin is 7×10^{-11}.

Perhaps the most interesting fact seen in these data (Fig. 3) is that the signal detected does <u>not</u> occur at exactly the expected frequency (that of Her X-1). Since the time base for collecting the data was a Rubidium atomic clock accurate to 1×10^{-11}, the uncertainty in the time base was orders of magnitude smaller than the effects seen in this experiment. Because the optical pulses could be caused by the excitation of the surface of the companion star by the X-ray source, or by the excitation of gas streams in the system, we do not necessarily expect the observed pulse frequency to correspond exactly to that of the X-ray source. It should of course be near the X-ray pulsar frequency, so we have (somewhat arbitrarily) looked for any signals in the frequency region defined by the Doppler shifts of the X-ray source.

We searched our power spectra for any significant peaks in this frequency range. Since the length of the runs varied, the number of bins searched varied, but was generally 6 or 12 bins. The statistical significance of power in any one of these bins is reduced when more than one bin is considered.

III. RESULTS

Figure 4a shows the distributions of our observations plotted against the binary phase and the date. The bars indicate the duration of the runs and the dots indicate when X-ray flux was present from Her X-1. When a significant amount of pulsed power was detected in the frequency region of

Her X-1, we assumed the frequency was established by the data and calculated the uncertainty in the power detected by using the statistical fluctuations expected in a single bin. Fig. 4b shows the power seen in each run expressed as a fraction of the maximum light intensity of the binary system (defined as 4000 counts/sec). The fraction thus defined was corrected for atmospheric extinction. The vertical bars represent the 67% confidence level region. Those runs where no significant signal was seen are also shown. The frequency of the excess power detected in those runs showing a significant signal is shown in Fig. 4c, which compares the observed frequency bin with the nominal and Doppler shifted Her X-1 frequency as a function of the phase of the binary system.

Table 1 is a summary of our data. Column 1 gives the run number, column 2 the time of the observation (JD-2440000.5), and column 3 the duration of the run. In runs where a signal was seen, if excess power was detected in more than one bin, the run was broken up to determine more accurately (if possible) when HZ Her was pulsing, and when it was not. The approximate fraction of the run with detectable pulsation is given in column 4. Column 5 gives the Her X-1 binary phase during the run. If the run was subdivided, the phase region when pulses were seen is shown in Fig. 4b. The amount of pulsed light, expressed as a fraction of the maximum light level of HZ Her is given in column 6. The probability of any bin in the frequency region searched exceeding (due to statistical fluctuations) the maximum power level found in that region is given in column 7. This is approximately the product of the number of bins considered with the single bin probability (e^{-x}). In Run 5 significant power was detected at three times the Her X-1 frequency. In this same run power was also seen at one-half the Her X-1 frequency, and in Run 13 power was detected at three-halves the pulsar frequency. These two runs suggest the possibility that the fundamental Her X-1 frequency is actually half that reported by Tananbaum et al. (1972). The likelihood that these fractional harmonics are simply statistical fluctuations is about 2%. The accuracy of the pulse frequency is specified by the duration of the observation. The center frequency of the bin with excess power and, in parentheses, its half width are given in column 8. This width simply represents the width of the bins in the Fourier transform and not a Gaussian error on the frequency. Signals at a particular frequency cannot appear in nearby frequency bins without also occurring much more strongly in the expected bin.

Our results do not conflict with those of Groth and Nelson (1972) if the variability of the pulse intensity is accepted. It is interesting to note that on the single observation date in common (Run 11), the power we see agrees rather well with the signal level reported by them (but not interpreted as a positive identification due to their lower sensitivity).

IV. CONCLUSIONS

The optical data from HZ Her are quite complex, but some definite conclusions can be made:

(1) HZ Her emits optical pulses

(2) These pulses are variable in intensity

(3) The frequency of pulsation is variable over a narrow range near that of the X-ray pulses.

We speculate that the pulsation seen is due to the excitation of the companion star by Her X-1 and/or the excitation of other matter in the binary system.

We tentatively conclude that the actual Her X-1 frequency is half that normally stated (98% confidence). There is a suggestion that the optical pulses are correlated with the presence of X-ray pulses (the 36 day cycle) but this is not certain at this time due to the paucity of optical pulsation data. An extensive observation program is currently under way.

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REFERENCES

1. Bahcall, J. N. and Bahcall, N. A. 1972, Ap.J. (Letters), 178, L1.

2. Davidsen, A., Henry, J. P., Middleditch, J. and Smith, H. E. 1972, Ap.J. (Letters), 177, L97.

3. Forman, W., Jones, C. A. and Liller, W. 1972, Ap.J. (Letters), 177, L103.

4. Groth, E. J. and Nelson, M. R. 1972, Ap.J. (Letters), 176, L111.

5. Lamb, D. Q. and Sorvari, J. M. 1972, I.A.U. Circ., No. 2422.

6. Liller, W. 1972, I.A.U. Circ., No. 2427.

7. Tananbaum, H., Gursky, H., Kellogg, E. M., Levinson, R., Schreir, E. and Giacconi, R. 1972, Ap.J. (Letters), 178, L1.

Table 1
Summary of Runs

Run Number (1)	Start of Observation JD-2440000.5 (2)	Duration of Run (min) (3)	Fraction of Run with Pulses (4)	Her X-1 Binary Phase (5)	Pulsed Fraction x 10^3 (6)	Accidental Probability (7)	Frequency Seen (8)
1	1519.200	175		299-325	.32	--	--
2	1520.214	175		153-179	.25	--	--
3	1526.220	70		353-002	.31	--	--
4	1532.207	175		172-197	-.35	--	--
5	1533.224	175	1/2	27- 52	1.51	3.4×10^{-5}	0.80795(9) 0.80833(9)
6	1534.214	175		236-262	.00	--	--
7a	1535.214	175	1.0	88-101	1.85	1.8×10^{-5}	0.80786(9)
7b				101-114	1.37		0.80786(39)
8	1536.224	88	1.0	302-315	1.14	4.5×10^{-2}	0.80738(9)
9	1537.249	44		156-163	.00	--	--
10	1540.203	263	1/3	65-103	1.75	7.2×10^{-6}	0.80833(9)
11	1545.272	175	1.0	58- 84	1.14	.053	0.80786(5)
12	1547.191	88	1.0	104-117	1.34	.40	0.80833(9)
13	1550.279	88	1.0	38- 51	1.40	3.0×10^{-3}	0.80776(9)
14	1553.168	175		294-320	.42	--	--
15	1562.178	263	1.0	37-75	.66	.26	0.80805(9)
16	1567.311	44		44-51	.00	--	--
17	1569.159	175	1.0	76-101	1.95	8.3×10^{-10}	0.80786(5)
18	1573.186	88	1.0	208-221	.94	.14	0.80786(9)
19	1574.147	263	1/3	51- 89	1.43	.12	0.80795(9)
20	1580.147	263	2/3	242-280	1.48	.012	0.80738(38)
21	1581.124	88	1	89-102	.81	.43	0.80795(9)
22	1709.473	88	1	266-279	1.50	7.2×10^{-3}	0.80738(9)

Fig. 1 The unnormalized power spectrum for Run 17 (9 Sept. 1972) where each bin plotted is the sum of 128 bins in the actual power spectrum. The detected signal at .80786 Hz is masked by the summing process.

Fig. 2. The distribution of binsversus power for Run 17. The histogram represents the experimental data and the solid line, the theoretically expected distribution which depends only on the total number of bins in the transform. The signal from HZ Her seen in the transform occurs in the bin farthest to the right.

Fig. 3. The power spectrum for Run 17 in the vicinity of the Her X-1 pulsar frequency. The power spectrum has been normalized so the mean level is one. The bin widths are 0.95367×10^{-4} Hz. The bin with excess power has a central frequency of .80786 Hz, while the Her X-1 frequency is .80826 Hz. The right hand vertical scale shows the probability of a single bin accidently exceeding the indicated power.

Fig. 4. (a) The extent (in Her X-1 binary phase) of 22 nights of observations on HZ Her plotted versus the dates of the observations (JD-2440000.5).

(b) The amount of light underneath a pure sine wave necessary to produce the excess power observed near the Her X-1 frequency in the runs, expressed as a fraction of the maximum light level of the HZ Her system. The vertical bars show the 67% confidence levels of these fractions. For Figs. 4a and 4b the dots represent the times when X-ray flux was present from Her X-1.

(c) The more significant results of Fig. 4b are plotted showing the precise phase and frequency regions of the observations and the expected (Doppler-shifted) Her X-1 frequency. The run number is shown for each box.

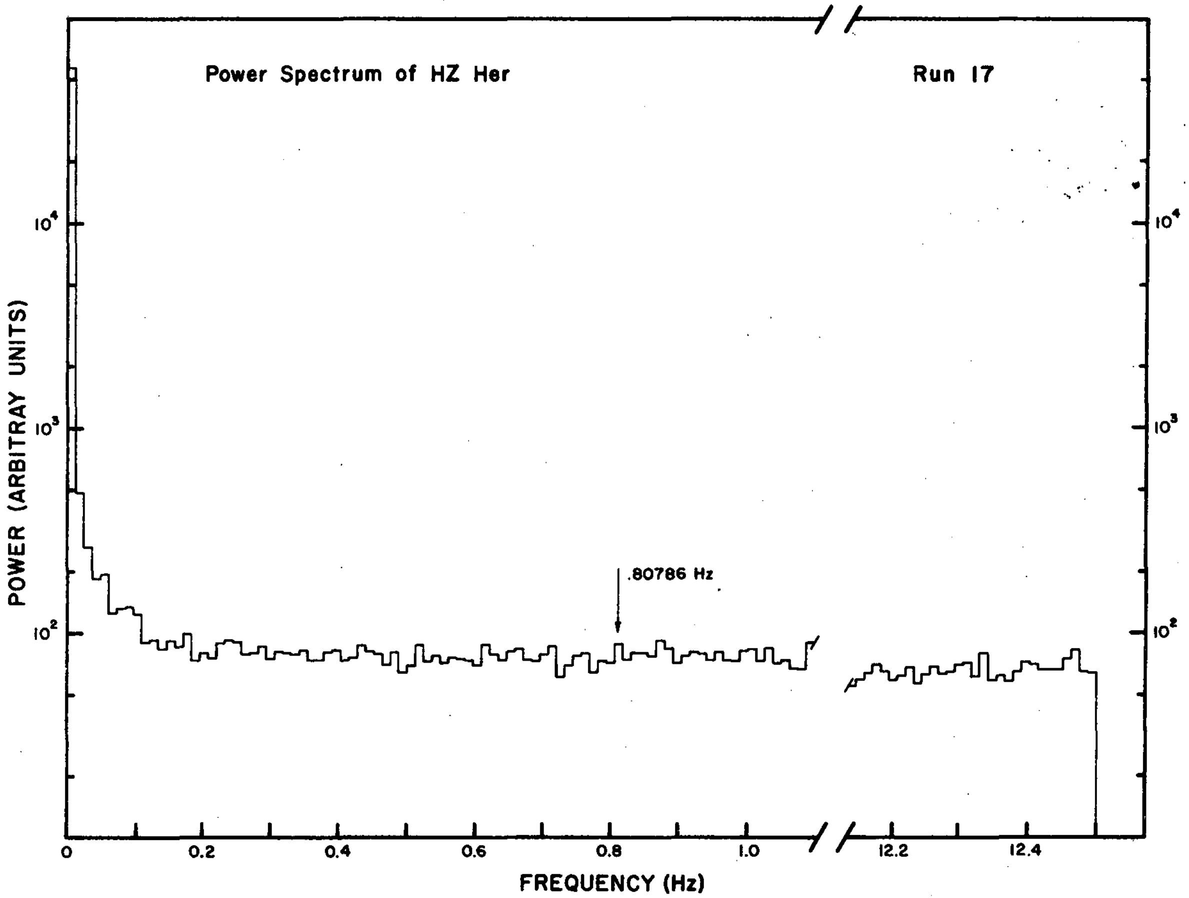

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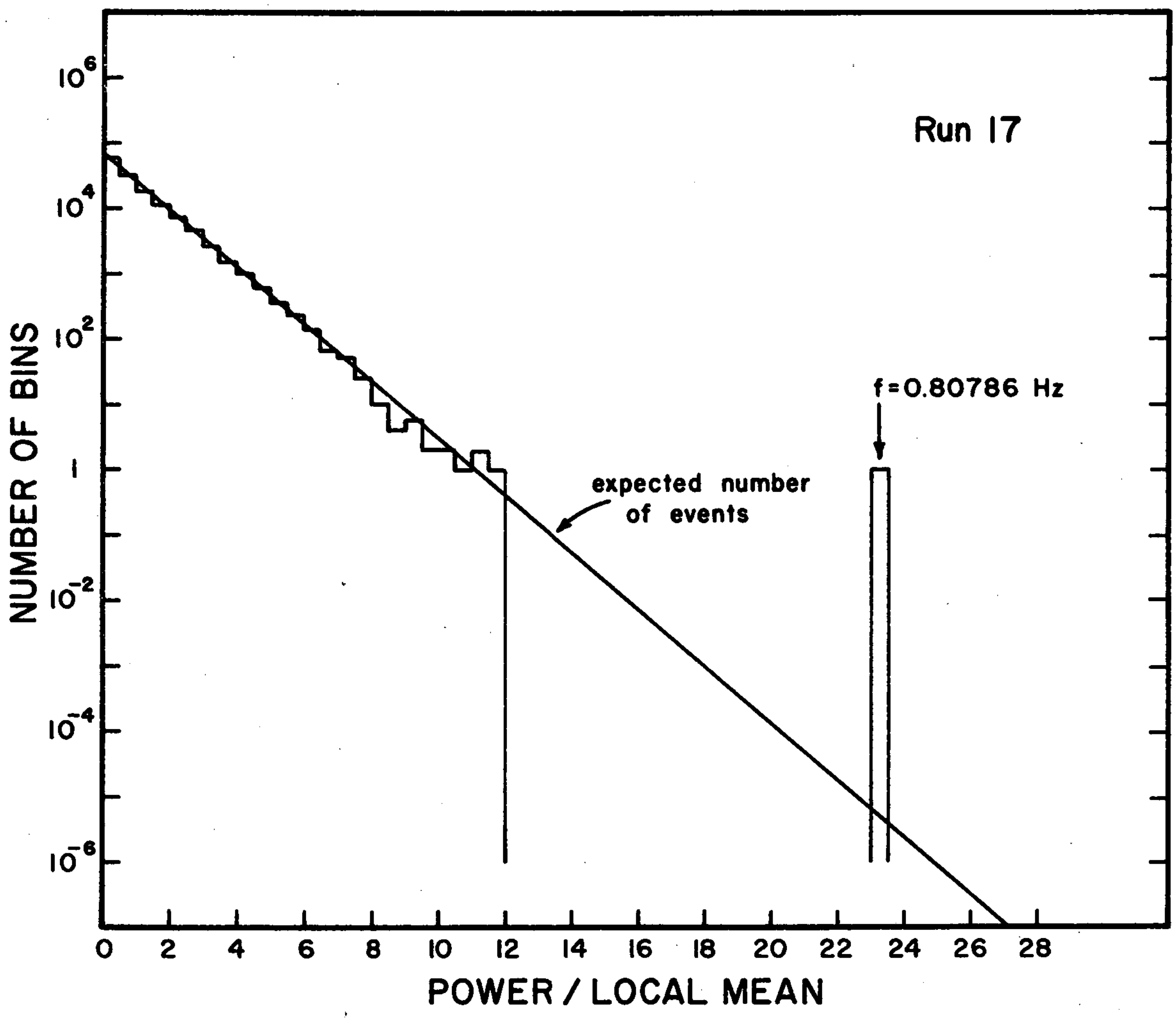
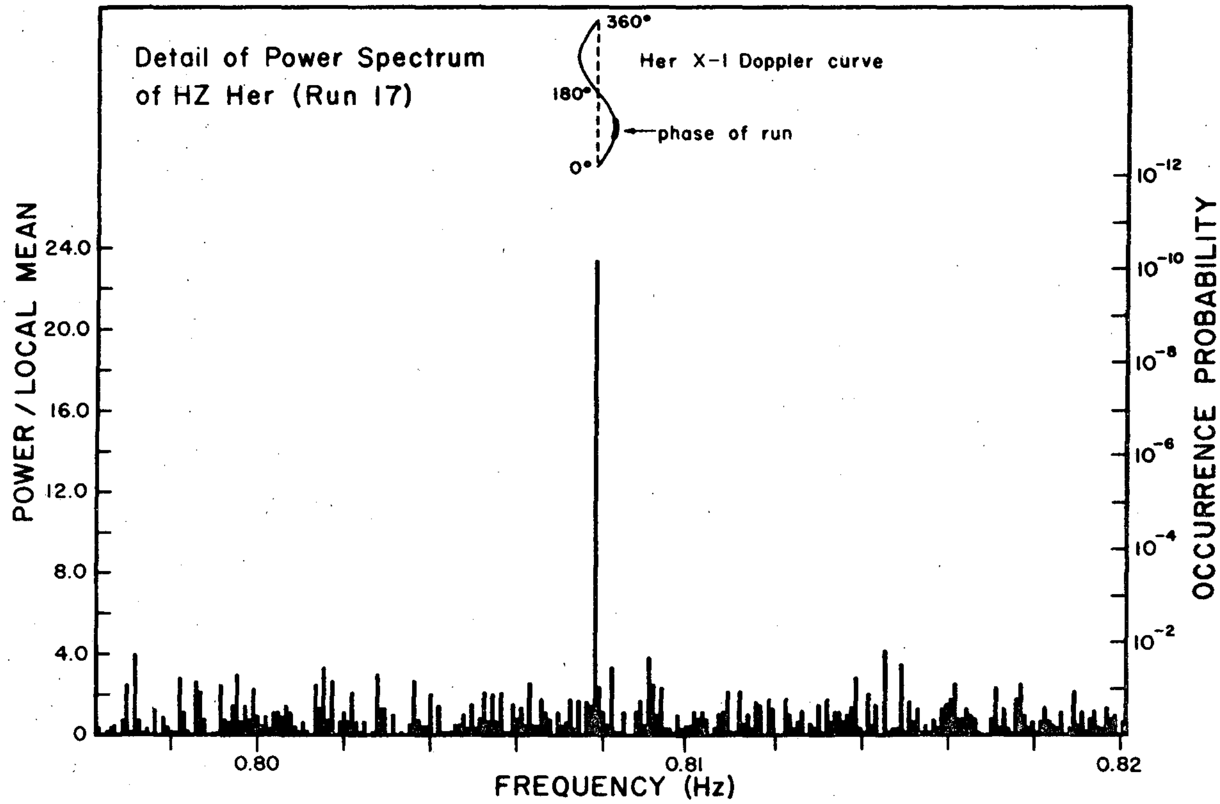
Fig. 1



XBL 732-153

Fig. 2



XBL 732-150

Fig. 3

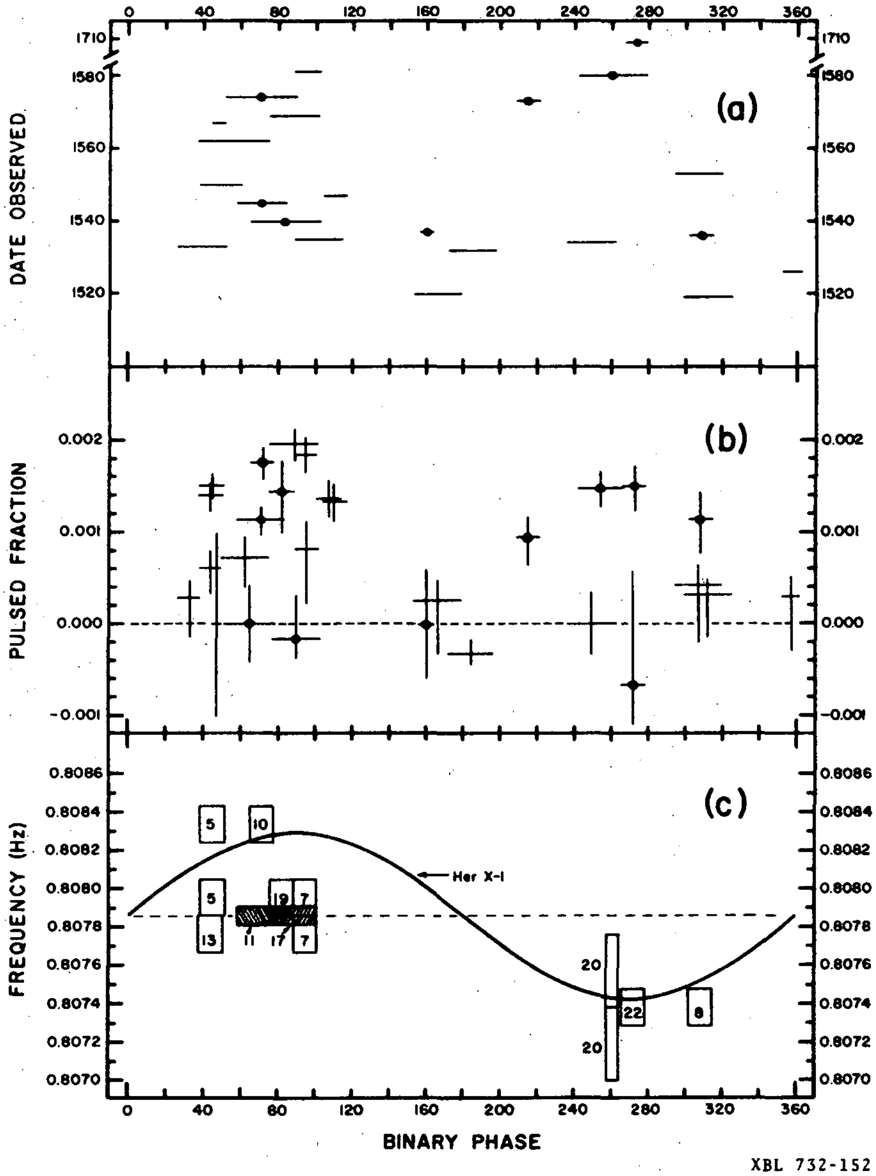

(a)
(b)
(c)
DATE OBSERVED
PULSED FRACTION
FREQUENCY (Hz)
BINARY PHASE
Her X-1
XBL 732-152

Fig. 4

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