THE ASTROPHYSICAL JOURNAL, 328:L9–L12, 1988 May 1

VHE GAMMA RAYS FROM HERCULES X-1[1]

L. K. RESVANIS
Physics Laboratory, The University of Athens

A. SZENTGYORGYI
Department of Physics, Columbia University

J. HUDSON, L. KELLEY, J. G. LEARNED, C. SINNIS, V. STENGER, AND D. D. WEEKS
Department of Physics, The University of Hawaii

J. GAIDOS, M. KERTZMAN, F. LOEFFLER, T. PALFREY, G. SEMBROSKI, AND C. WILSON
Department of Physics, Purdue University

AND

U. CAMERINI, J. P. FINLEY, W. FRY, J. JENNINGS, A. KENTER, M. LOMPERSKI, R. LOVELESS, R. MARCH,
J. MATTHEWS, R. MORSE, D. REEDER, AND P. SLANE
Department of Physics, The University of Wisconsin, Madison

Received 1987 December 10; accepted 1988 February 10

ABSTRACT

Her X-1 was observed for 104 hr of good conditions in a search for TeV-range gamma rays, in 1986 May–July, at the Haleakala Gamma Observatory. On May 13 a burst of activity of approximately 15 minutes duration was detected, with a period of 1.23593 ± 0.00018 s. Although this period differs significantly from the pulsar period expected from X-ray observations, it is consistent with measurements of the periodicity of VHE and UHE gamma rays by other observers that summer.

Subject headings: gamma rays: general — pulsars — X-rays: sources

I. INTRODUCTION

The Her X-1/HZ Her system is one of the best studied X-ray binary pulsar systems. The orbital parameters have been well determined by X-ray observations (Joss *et al.* 1980; Deeter, Boynton, and Pravdo 1983) and the pulsar period of ~ 1.24 s has been measured using both direct X-radiation from the neutron star and secondary optical radiation presumed to originate from X-ray reprocessing in the atmosphere of the companion star (Davidsen *et al.* 1972).

While X-ray observations reveal that the average behavior of the period shows the familiar spin-up found in many accreting binary systems, from time to time significant deviations from the steady linear decrease of period have been observed, of magnitude several parts per million (Giacconi 1974).

In addition to orbital and pulsar periodicities, the binary system exhibits a 35 day periodicity (Tananbaum *et al.* 1972), with nearly all emission concentrated in two peaks that differ in intensity by roughly a factor of 2. The dynamical origin of this periodicity is not yet well understood, although it has been attributed to precession, either of the neutron star (Trümper *et al.* 1986) or of the accretion disk of matter from the companion star (Katz 1973).

Episodes of TeV gamma-ray emission from Her X-1 have been reported by several observers (Dowthwaite *et al.* 1984; Baltrusaitis *et al.* 1985; Gorham *et al.* 1986*a*, *b*). The distribution in orbital and 35 day phases of these emissions is shown in Figure 1*a*. The episodes of emission are all confined with the "on" phases of the 35 day periodicity.

II. OBSERVATION

The Haleakala Gamma Observatory (HGO) (Resvanis *et al.* 1988) logged 132 hr of observation time on Her X-1 between the months of May and July in 1986. After rejection of weather-affected data, 104 hr were selected for analysis. The range of orbital and 35 day phases covered by these data is shown in Figure 1*b*.

The HGO telescope detects gamma-ray atmospheric cascades above ~ 200 GeV primary energy by means of their atmospheric Cerenkov radiation. It is provided with two identically instrumented apertures, one of which was directed at the source, and the other separated from it by 3°6 in declination to monitor background. In the search for signal, both on-source and off-source data were treated identically.

III. ANALYSIS

For purposes of analysis, data were subdivided into segments of 15 minutes duration, chosen as the shortest interval likely to yield a statistically significant signal at the fluxes reported by other TeV gamma-ray observers. Event rates in both apertures were fitted to a three-term Legendre polynomial in zenith angle to establish a baseline for detecting fluctuations. In addition, a Rayleigh test for pulsar periodicity was performed, with 17 trial periods centered on the expected X-ray period. These represented only three Fourier-independent periods, i.e., periods separated by $\delta p = p^2/t$, where

[1] Supported in part by United States Department of Energy contracts AC02-76ER01428, AM03-76SF00235, AC02-76ER00881, and by the Wisconsin Alumni Research Foundation.

p is the period and t is the duration of observation. Thus the period search represents an "oversampling."

The largest on-source signal, with Rayleigh parameter $z = 12.79$, was found in an interval starting at $13^h35^m40^s.98$ UTC on May 13, at orbital phase $\phi_{orb} = 0.81$ and 35 day phase estimated at $\phi_{35d} = 0.22$. The event rate in this interval was above the baseline by 6%, or 1.4 standard deviations. Though the value of z would be the mean value expected for a signal in excess of 20% of the background, the two tests are statistically compatible.

The power spectrum is shown in Figure 2*a*, and the light curve, in Figure 2*b*. The excess above background corresponds to a flux of $\sim 5 \times 10^{-10}$ cm^{-2} s^{-1}, which is within the range of fluxes reported in earlier observations. The power spectrum is extended to 10 Fourier-independent periods for purposes of illustration.

The observed period of 1.23593 ± 0.00018 s is 0.15% lower than 1.237778 s, the value expected by extrapolation from the most recent X-ray ephemeris. Our measurement is, however, in excellent agreement with an observation at the Whipple Observatory in 1986 June (Lamb *et al.* 1987). An episode observed at the Cygnus Air Shower Array in 1986 July (Dingus *et al.* 1987; Protheroe 1987) is also consistent with this reduced period. The Cygnus array has an energy threshold above 10 TeV, two orders of magnitude higher than that of the HGO telescope. Measurements of secondary optical emissions from HZ Her were taken on three different occasions during 1986 (Middleditch 1987) and the observed periodicities were within 5×10^{-5} s, or four parts in 10^5, of the extrapolated X-ray period. These results are compared to X-ray and earlier gamma-ray observations in Figure 3.

As a test against the null hypothesis, we calculate the probability W that our result represents a random fluctuation in the rate of hadronic cosmic-ray events:

$$W = Q(1 - \ln Q) ,$$

where

$$Q = [1 - (1 - p_1)^N]p_2 .$$

Here p_1 is the probability of obtaining $z > 12.73$, p_2 is the probability of obtaining a rate excess larger than 1.4 σ, and N is the number of independent trial searches performed. Our 416 intervals were each sampled over a range of three Fourier-independent trial periods. Monte Carlo studies of statistical fluctuations in the Rayleigh parameter (De Jager 1987) indicate that oversampling the period by a factor of 6 carries a statistical penalty of about 3, i.e., the effective number of trials is about 3 times the number of Fourier-independent periods. Thus $N \approx 3 \times 3 \times 416 = 3744$. This yields a total chance probability of $W = 6.8 \times 10^{-3}$. By contrast, the lowest value of W for any of the off-source intervals was 0.385.

In summary, we observe VHE gamma rays from Her X-1 with a period that is incompatible with the extrapolated X-ray pulsar and observed optical periods, but compatible with other VHE and UHE gamma-ray observations within a few months of ours. The shift is two orders of magnitude greater than the transient changes observed in X-rays, and 2.8 times the maximum orbital Doppler effect, so it seems unlikely that we are directly observing the pulsar period. It may be possible that the secondary mechanism that produces this shift operates primarily during the brief episodes of VHE gamma-ray emission that surpass the detection threshold. Episodes with period deviations this large may have been present in earlier observations, but were missed because the period search had too narrow a range of trial periods. It may prove useful to reexamine old data on this source.

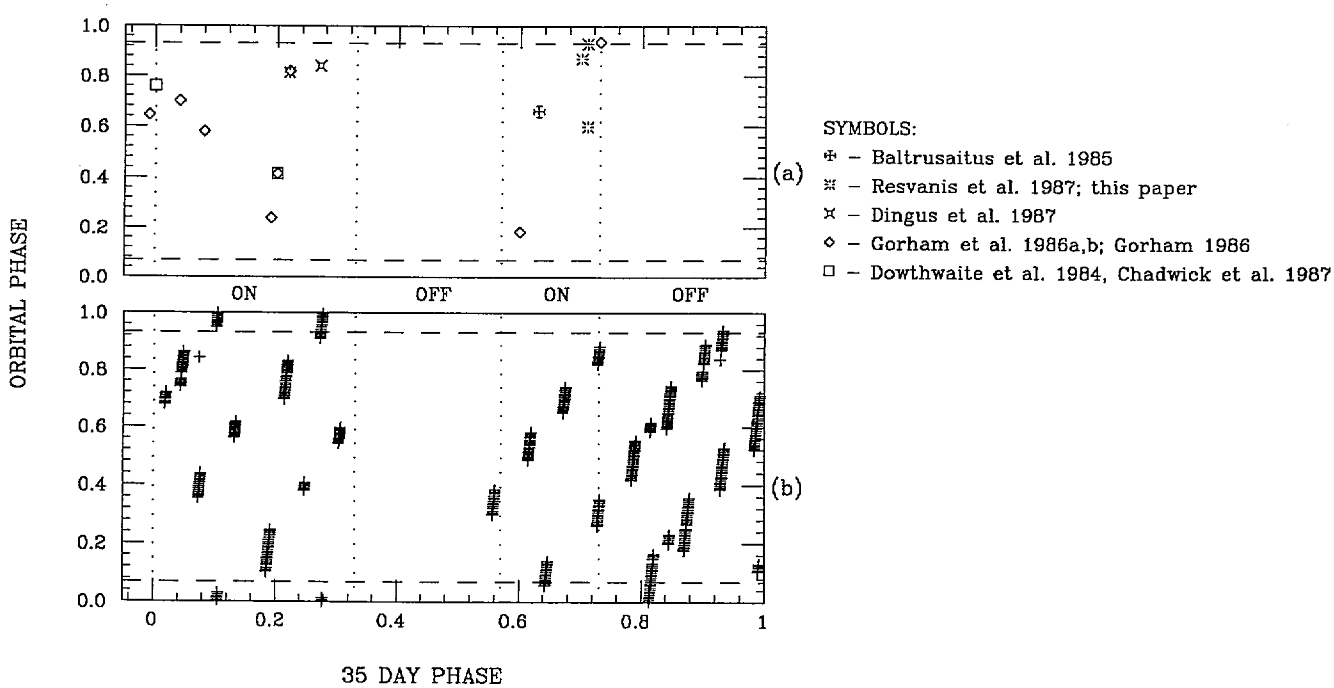

FIG. 1.—(*a*) Observations of TeV gamma rays from Her X-1. Note the relative absence of detections in the "off" regions of the 35 day cycle. (*b*) Orbital and 35 day phase distribution of observation times at HGO in 1986 May–July.

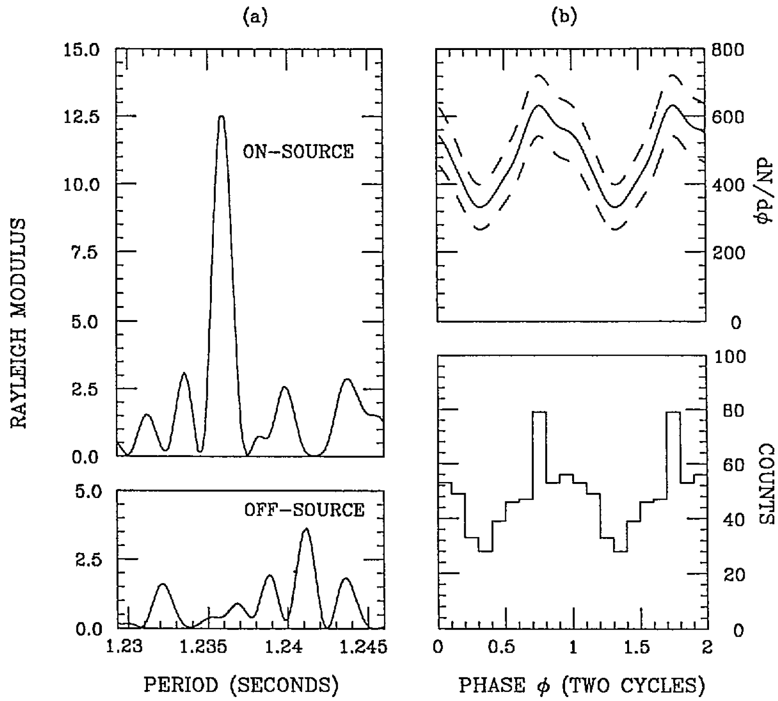

FIG. 2.—(*a*) Power spectra on and off source for gamma-ray burst; (*b*) Histogram of data folded with period 1.23593 s. The upper curve was derived from the data in the lower by the normal kernel density estimator method (de Jager 1987).

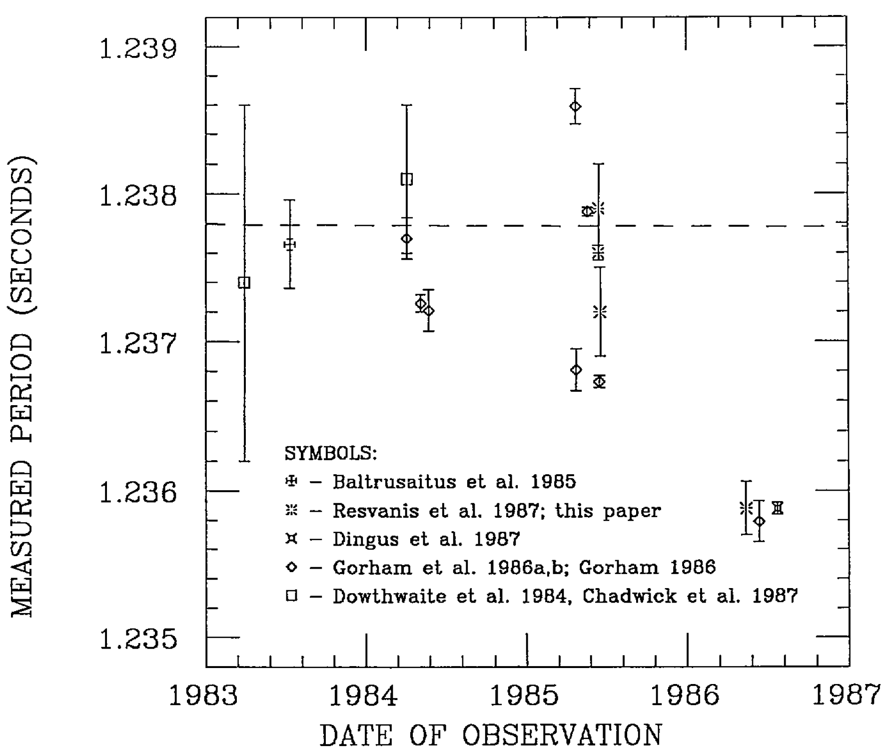

FIG. 3.—Distribution of measured periods for Her X-1 in TeV gamma-ray detections

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U. Camerini, J. P. Finley, W. Fry, J. Jennings, A. Kenter, M. Lomperski, R. Loveless, R. March, R. Morse, D. Reeder, and P. Slane: Department of Physics, The University of Wisconsin, Madison, WI 53706

J. Gaidos, M. Kertzman, F. Loeffler, T. Palfrey, G. Sembroski, and C. Wilson: Department of Physics, Purdue University, West Lafayette, IN 47907

J. Hudson, L. Kelley, J. G. Learned, C. Sinnis, V. Stenger, and D. D. Weeks: Department of Physics, The University of Hawaii, Honolulu, HI 96822

J. Matthews: Department of Physics, University of Michigan, Ann Arbor, MI 48109

L. K. Resvanis: Physics Laboratory, The University of Athens, 10680 Athens, Greece

A. Szentgyorgyi: Department of Physics, Columbia University, New York, NY 10027