Hercules X-1: Pulsed γ-rays Detected Above 150 GeV

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1.Introduction. The 1.24 second binary pulsar Her X-1, first observed in x-rays in 1971 by UHURU (Tananbaum, et al 1972) has now been seen as a sporadic γ-ray source from 1 TeV up to at least 500 TeV (Dowthwaite, et al 1984; Baltrusaitis, et al 1985). In addition, reprocessed optical and infrared pulses are seen from the companion star HZ Herculis (Middleditch, Pennypacker, and Burns, 1983). Thus measurements of the Her X-1/HZ Herculis system span 15 decades in energy, rivaling both the Crab pulsar and Cygnus X-3 in this respect for a discrete galactic source.

In both of the previous reported observations of γ-rays from Her X-1, the photons were detected by observing the extensive air showers produced by interaction with the upper atmosphere. In April 1983, Dowthwaite,et al,(1984) observed a burst of emission lasting 3 min. which may have been associated with a transition of the pulsar from the x-ray low flux state to a high flux state in the 35 day cycle. About 1 month later the satellite Tenma observed Her X-1 in a high-flux state (Nagase,et al 1984a). Initially they found the pulsar light curve to be similar to previous observations; however, during the latter part of the observation, the flux became strongly diminished and the pulses began to slip in phase, arriving progressively earlier at a rate of about 18 ms/hr (Nagase, et al, 1984b). Thirty-seven days after the Tenma observation, EXOSAT was unable the detect Her X-1 in an expected high flux state, and approximately eight 35 day cycles elapsed before the high state was seen again (Parmar, et al, 1985).

During mid-July 1983, early in this extended x-ray low state, the Fly's Eye detector in Utah observed a flux of pulsed γ-rays of $E > 500$ TeV from Her X-1 during a 40 min. interval (Baltrusaitis,et al 1985). We observed Her X-1 during the spring of 1984, soon after the cessation of the extended x-ray low state. We have found, at the 99.98% C.L., strong periodic emission of similar character to that reported by Dowthwaite, et al (1984). In addition, comparison of EAS images from the direction of Her X-1 with those of background regions indicate with 98% confidence that the emission persists at a weaker level throughout the ~30 hour data set, although we cannot yet estimate what fraction of this may be pulsed.

2.Observations. The F.L. Whipple observatory 10 meter reflector was used to observe Her X-1 during four successive moonless periods from March-June 1984 (see Cawley, et al, 1985, OGG 9.5-4, for details of data aquisition and techniques). The observing sequence included a 28 minute ON-source segment, preceded or followed by an equal length background segment which covered the same range of elevation and azimuth as the source run. Times of arrival of extensive air shower (EAS)-initiated events were digitized to 1 μsec, with a WWVB clock providing an absolute reference, to a precision of about .5 msec. The data include 37 pixel images (.4^{o} per pixel) of each shower which can be used for independent selection of possible γ-rays out of the sample; this will be discussed further below.

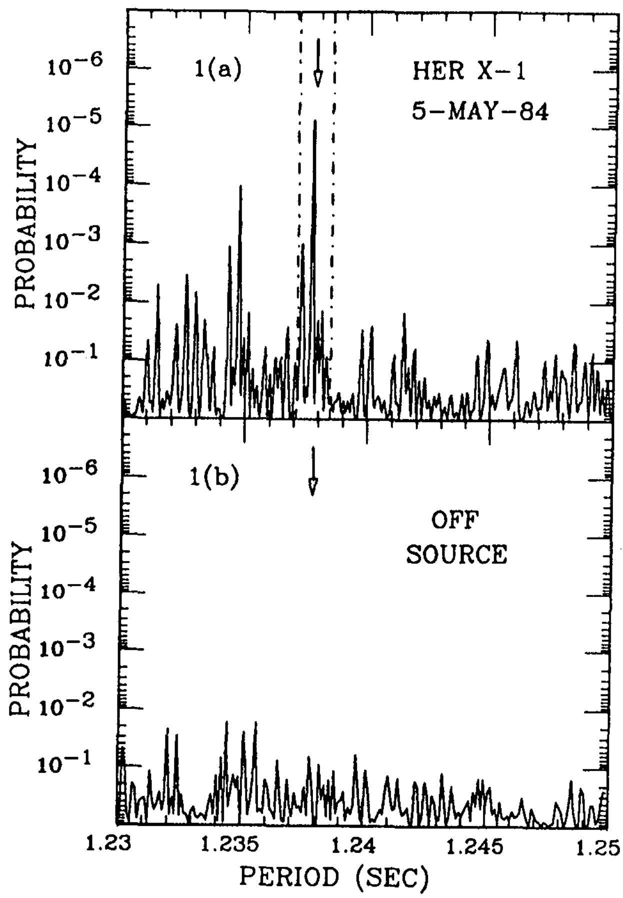

Fig. 1: (a) Periodogram for data from night of 5-May-1984, orbital phase .53-.61 The vertical dashed lines indicate the range of possible Doppler shifts for Her X-1 over one orbit. (b) periodogram for off-source data, taken alternately with on-source data. Arrows mark expected x-ray period.

Because of possible short time-scale variations of the period such as those found by Nagase, et al (1984b) we searched each 28 min data run individually for evidence of 1.24 sec pulsation. The times were first corrected to the solar system barycenter, using the formula of Deeter,Boynton, and Pravdo (1981), which was checked against a much more accurate method and found to produce no error greater than 50 ms. An estimate of the Fourier power spectrum for each 28 min run was then made in the neighborhood of the 1.24 sec period using a periodogram technique (see Scargle, 1983). In two of the periodograms, on 4 April and 5 May, 1984, a peak was seen near the x-ray period as derived from a concurrent EXOSAT ephemeris (Trumper, et al 1985). In each case the peak power was about seven times the mean noise power level. In addition, the run on 5 May was preceded by two other runs with similar peaks of lower amplitude. When the entire time series for that night was analyzed, the power level of the peak increased to about 12 times the noise power level, indicating that the emission was persistent throughout that night's observation, reaching a maximum level near the end of our observing period. Fig. 1a shows the periodogram for that night's data with spectral power converted to probability as prob = $\exp(-P(\omega))$ (Scargle,1983).The vertical dashed lines show the range of Doppler shifts that are possible for the orbital velocity of Her X-1. The chance probability at the peak power is 8×10^{-6}, which is reduced to an overall chance probability of 2×10^{-4}, by multiplying in the number of observing nights (24). Figure 1b shows the periodogram for the background

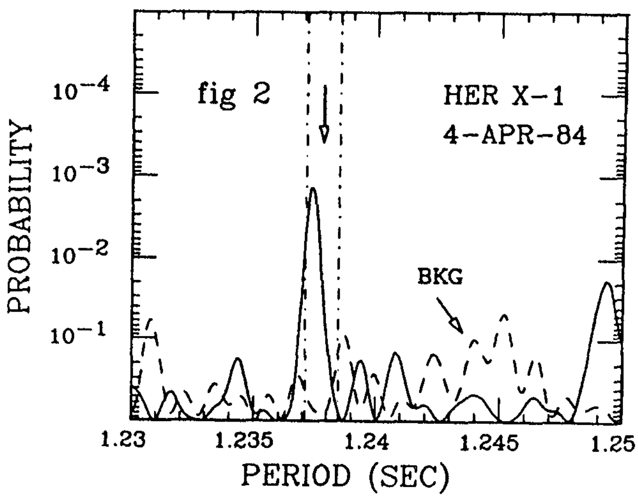

Fig. 2: Periodogram for a single 28 min run on 4-Apr-84, and its associated background run (shown in dashed lines). The vertical dot-dash lines indicate the range of possible Doppler shifts for Her X-1 over one orbit. This run was at orbital phase 0.42. Arrow marks expected x-ray period.

runs, which were taken alternately with the on-source runs, making it difficult for any spurious systematics to go undetected. The non-statistical noisiness and sidebands in the spectrum in fig. 1a appear to be due to the uneven sampling, which causes power at the fundamental to "leak" off to other frequencies (Deeming, 1975; Ferraz-Mello, 1981). Thus we have not attempted to assess possible Doppler shifts in the periods, since our signal-to-noise ratio is not high enough to assure the required accuracy in the period determination using the periodogram method.

Fig. 2 shows the periodogram for the run on 4 April, with the background periodogram shown in dashed lines. The emission on this night appears to be confined to a single 28 min. interval, during which it appears to be uniform. This run was the last of the night, so we cannot say if the emission persisted beyond this observation. The increased width of the peaks here is due to the shorter observation time. Although the statistical significance of this observation is much less than that of 5-May-84, the similarites in the emission duration and flux, and the light curve support its inclusion in this report.

Using the 37 pixel pulse-height information for each EAS event, we employed imaging techniques (see Hillas, 1985, OGG 9.5-3; and Cawley, et al, 1985, OGG 9.5-4; this proceedings) to enrich the γ-ray/bkg. fraction in our data before determining the average light curves. Fig. 3 then shows the light curves when the data are folded at the most probable period for each run (both of which were within 1 σ of the expected period). The absolute phase is arbitrary, since existing x-ray ephemerides were not sufficiently accurate to preserve absolute phase up to our observing epoch, or over the month separating the observations. The dashed line gives the mean background level after the image cuts were applied to the off-source data as well. The time-averaged fluxes are estimated to be:

4-Apr-84: $F = (5.8 \pm 2.1) \times 10^{-10}$ photons $cm^{-2}\ s^{-1}$, $\Delta t > 28$ min

5-May-84: $F = (6.6 \pm 1.2) \times 10^{-10}$ photons $cm^{-2}\ s^{-1}$, $\Delta t > 3$ hrs

both for energies above 150 GeV.

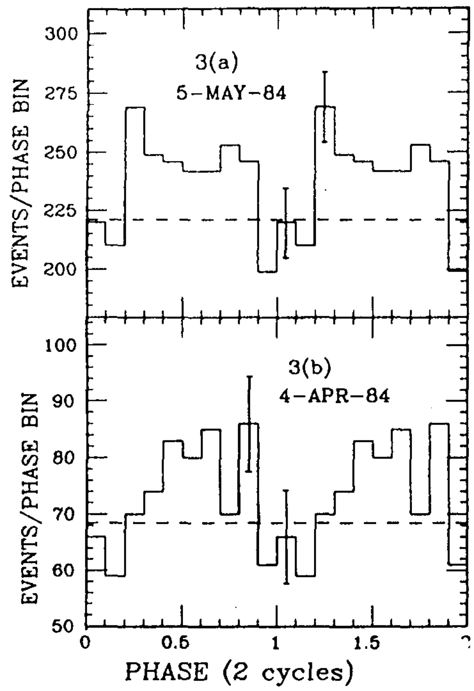

Fig 3.(a),(b) Light curves for the dates shown, enriched data sample. Phases are arbitrary, and errors are statistical only.

3.Discussion. The orbital phase of the data taken on 5-May-84 was .53-.61, and the emission appears to have increased throughout the observation. The phase of the 4-April-84 data is .42. Thus there is no strong correlation in orbital phase with other γ-ray observations (Dowthwaite, et al, saw phase .75; Baltrusaitas, et al, phase .66). Orbital phase 0.55 is associated (Crosa and Boynton, 1980) with the beginning of "anomalous dips" in the x-ray flux, occuring usually one or two orbits after the 35 day turn on. These are attributed to mass exchange events in which matter arriving from the companion star begins circulating around the accretion disk, gradually relaxing in scale height over approximately 20% of an orbit. The 5-May-84 observation was very near to expected 35 day turn-on, as extrapolated from EXOSAT and Tenma observations before the extended low; however, we are not aware of the exact phases after the cessation of the low. If the observation were concurrent with an anomalous dip event, it could be associated with the availability of target matter above the edge of the accretion disk for high energy particles , which then cascaded to form photon secondaries. The apparent variation and transience of the emission could thus be explained by the changing column density of the target matter as it relaxed into the disk. We intend to further investigate any correlations with concurrent x-ray observations as reports of these become available.

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