500 TeV GAMMA RAYS FROM HERCULES X-1

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ABSTRACT

A signal (chance probability = 2×10^{-4}) with the 1.24 s period of Hercules X-1 has been observed using the Utah Fly's Eye. The signal's relatively long period and high shower energy conflict with some popular models of particle acceleration by pulsars. Optical and X-ray data suggest a picture in which energetic particles produce multi-TeV γ-rays by collisions with Hercules X-1's accretion disk.

1. Introduction. A detection of TeV γ-ray emission by Hercules X-1 has been reported by Dowthwaite et al. (1984). We have studied the same object at much higher energies by detecting Cerenkov flashes from atmospheric air showers. The use of the Fly's Eye to search for ultra-high energy γ-rays has been described elsewhere (Boone et al. 1984). The 67 mirror units and 880 photomultiplier tubes of Fly's Eye I recorded Cerenkov flashes which triggered 6 or more tubes. This selected showers with energies above about 200 TeV, with mean energies near 500 TeV. The angular resolution radius is about 3.5°, therefore a 7° square target region was used centered on the direction of Hercules X-1.

2. Observations and Data Analysis. The only nights for which Hercules X-1 was visible and the detector was recording Cerenkov data were July 10-14, 1983 (UT). Expected rates within the target region (if γ-ray emission were absent) were found by observing rates in regions outside the target region in the same declination strip. The total number of showers recorded in the target region was 301, with an expected number of 271.9. This amounts to a 1.8σ excess. A more significant result is obtained by a test for periodicity in the data. Because Dowthwaite et al. (1984) observed very sporadic emission from Hercules X-1, the data from the 5 nights were analyzed separately. The shower arrival times were corrected for the motion of the X-ray source in its binary system and adjusted to the solar system barycenter using results from Deeter, Boynton, and Pravdo (1981). The pulse period was obtained from 1983 May X-ray satellite results by extrapolation, using the period and period derivative given by Nagase et al. (1984). The period used to fold the data was 1.2377872 s. Although the X-ray data obtained a period, an absolute phase determination was not possible. Our choice of phase is arbitrary.

A χ^2 test was applied to the distribution of phases within the ~1.24 s period, or light curve. Using 10 phase bins the data were compared to a constant background prediction. To remove effects of arbitrary bin boundaries, four χ^2 values were obtained for each data set by uniform shifts of the phase bin boundaries. Then the maximum χ^2 was selected. This procedure prevented a narrow signal from being split between adjacent bins and thereby diminishing its apparent significance. Of the 5 nights, only 1983 July 11 had a statistically significant χ^2. Next, the data from that night were divided into two equal parts and it was observed that the signal was present only in the data taken in the earlier part of the night. The light curve for this case is shown in Figure 1. An excess is present in only one bin. The uncertainty in the background is very small and the Poisson probability for excess counts to be due to background fluctuations is found to be 7 x 10^{-7}. The number of tries used in getting this result is the product of the number of bins (10), the number of phase increments (4), and the number of data sets tried (5 nights and 2 half nights). This gives 280 tries, yielding a chance probability of 2×10^{-4}.

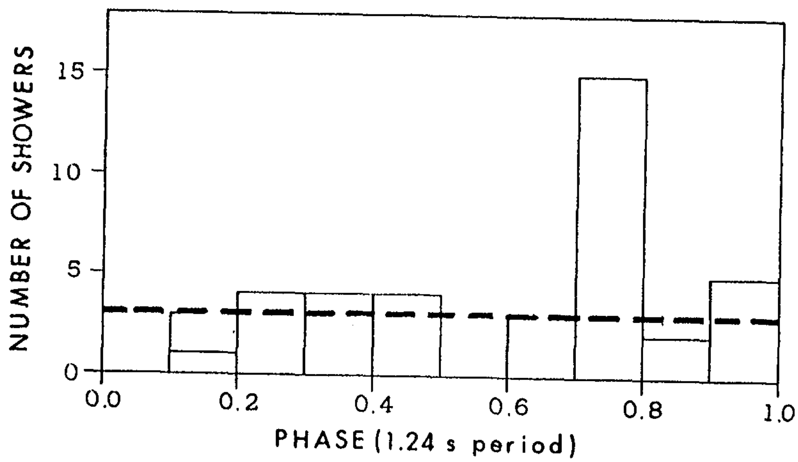

Fig. 1 Phase dependence of the shower arrival times. The dashed line is the expected number.

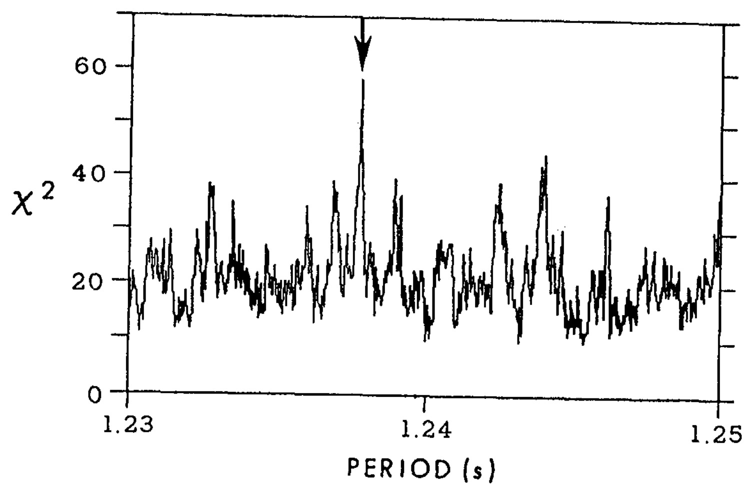

Fig. 2 The χ^2 dependence on the period used to fold the data. The arrow marks the period obtained from Nagase et al. 1984.

3. Results.

A fixed value of the period was used while performing the χ^2 tests described above. Figure 2, however, shows the χ^2 as a function of the period. The χ^2 is quite specific in preferring a period near that of Nagase et al. (1984). Since the signal was received during a relatively short 40 minute interval, the period measurement is crude compared with other experiments. The barycentric time at the center of this time interval was JD 2445526.719. This corresponds to orbital phase 0.66 (Deeter, Boynton, and Pravdo 1981) and 0.63 in the 35 day period (Delgado, Schmidt, and Thomas 1983). The orbital phase is such that the companion star, HZ Herculis, was not near the line of sight to the pulsar. It was therefore not positioned so that the edge of its atmosphere could serve as a target or converter to produce high energy γ-rays from energetic protons.

The approximate γ-ray flux was estimated using the signal shown in Figure 1. The resulting flux is $3.3 \pm 1.1 \times 10^{-12} cm^{-2} s^{-1}$. This is the (apparently sporadic) flux observed in the first part of the 1983 July 11 data. It is the average flux within the 1.24 s period. The uncertainties given above are statistical, only. Using a distance of 5 kpc for Hercules X-1 and assuming the γ-rays are emitted isotropically, the peak observed luminosity above 5×10^{14} eV is about 10^{37} erg s^{-1}. This value is close to the total luminosity estimated for the system (Bradt et al. 1979).

4. Discussion. The charged particles which produced these γ-rays must have energies above 10^{15} eV. Given the relatively long rotational period (1.24 s) of Hercules X-1, this energy exceeds the maximum expected from Hercules X-1 according to certain acceleration models. The magnetic field in the vicinity of the pulsar surface is $3\text{-}5 \times 10^{12}$ Gauss (Trümper et al. 1978). According to the models of Goldreich and and Julian (1969), and Cheng and Ruderman (1977), the maximum energy of produced particles would be about $2\text{-}3 \times 10^{13}$ eV. If we assume the model of Gunn and Ostriker (1969) and allow particles to be accelerated from the speed of light cylinder radius out to the companion star, the maximum energy is near 10^{13} eV. Some models, however, do predict sufficiently high energies from this system (Kundt 1983, Chanmugam and Brecher 1984).

Optical (Delgado, Schmidt, and Thomas 1983) and X-ray (Parmar et al. 1985) data from Hercules X-1 were taken during the time interval of our observations. Hercules X-1 displays a 35 day cycle of X-ray intensity variations in addition to the 1.24 s pulsar period and the 1.7 day orbital period. High emission normally occurs during about 10 days of the cycle. During 1983 June to August, however, Hercules X-1 remained at levels < 5% of the normal peak intensities. This might suggest that X-ray production did not occur during this time. This conclusion is not supported by optical observations made in 1983 June and August. These show the normal (~1.5 mag) variation of the optical emission in the 1.7 day orbital cycle. This variation is attributed to extra emission due to X-ray heating of the side of the companion star which faces the X-ray source. The optical variability implies that X-rays were being produced during this interval. The conclusion of Parmar et al. and Delgado, Schmidt, and Thomas was that the accretion disk may have thickened and blocked the line of sight to the earth for X-rays originating near the neutron star.

If energetic protons are produced near the neutron star, then the occulting material mentioned above may have served as target material for the generation of ultra-high energy π° mesons which decayed to produce the energetic γ-rays. The resulting γ-rays are essentially parallel with the parent protons. The γ-rays could be produced reasonably efficiently by column thicknesses of 5-200 g/cm^{-2}, which would absorb keV X-rays very effectively. Such a model may be rejected in the future if ultra-high energy γ-rays are detected simultaneously with X-rays. If the model is correct the γ-ray emission by Hercules X-1 may occur only during unusual conditions.

Although the signal reported by Dowthwaite et al. (1984) was at much lower energy and was not simultaneous with our signal, our result is supportive of their conclusion that TeV γ-rays are produced by Hercules X-1.

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