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EVIDENCE FOR 500 TeV GAMMA-RAY EMISSION FROM HERCULES X-1

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ABSTRACT

A signal (chance probability = 2×10^{-4}) with a 1.24 s period has been observed from the direction of Hercules X-1. 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 support our picture in which energetic particles produce multi–TeV γ-rays by collisions with Hercules X-1's accretion disk.

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

A detection of TeV γ-ray emission by Hercules X-1 has been reported by Dowthwaite *et al.* (1984). We have analyzed data taken by the Fly's Eye to search for evidence of the same object at much higher energies. The experiment detected Cerenkov flashes from small 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). For the data described here, the 67 mirror units and 880 photomultiplier tubes of the Fly's Eye recorded Cerenkov flashes which triggered six or more tubes. This requirement selects 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. The data rate decreases rapidly at zenith angles greater than about 30° and is about 60 events per hour within the target region when the zenith angle is at its minimum value. 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 Fly's Eye has normally been triggered in a mode which rejects the numerous Cerenkov flashes. However, the trigger can be modified to record these flashes. The only nights for which Hercules X-1 was visible and the detector was recording Cerenkov data were 1983 July 10–14 (UT). The total number of showers recorded was 301, with an expected number of 271.9. This amounts to a 1.8 σ 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 five 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, it did not give an absolute phase. Consequently, our choice of phase is arbitrary.

A χ^2 test was applied to the distribution of phases within the $\sim$ 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 five nights, only 1983 July 11 had a 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. The χ^2 is 58.4 for 10 degrees of freedom. Because the number of showers in each bin is small, the χ^2 significance is not easily evaluated. The figure shows that 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 7×10^{-7}. The number of tries used in getting this result is obtained by taking the product of the number of bins (10), the number of phase increments (four), and the number of data sets tried (five nights and two half-nights). The number of tries is 280, yielding a probability of such a bin equal to 2×10^{-4}, or a confidence level of 99.98%.

A fixed value of the period was used while performing the χ^2 tests described above. Figure 2 shows the χ^2 as a function of the period. It can be seen that the χ^2 tests on the first half of the 1983 July 11 data are 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 2,445,526.719. 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

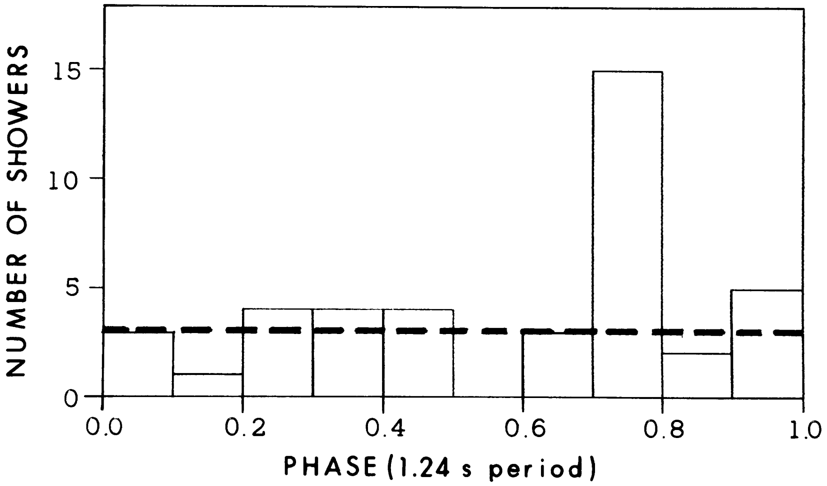

FIG. 1.—Phase dependence of the shower arrival times for the first half of the data received on 1983 July 11. The dashed line is the expected number of events in each bin.

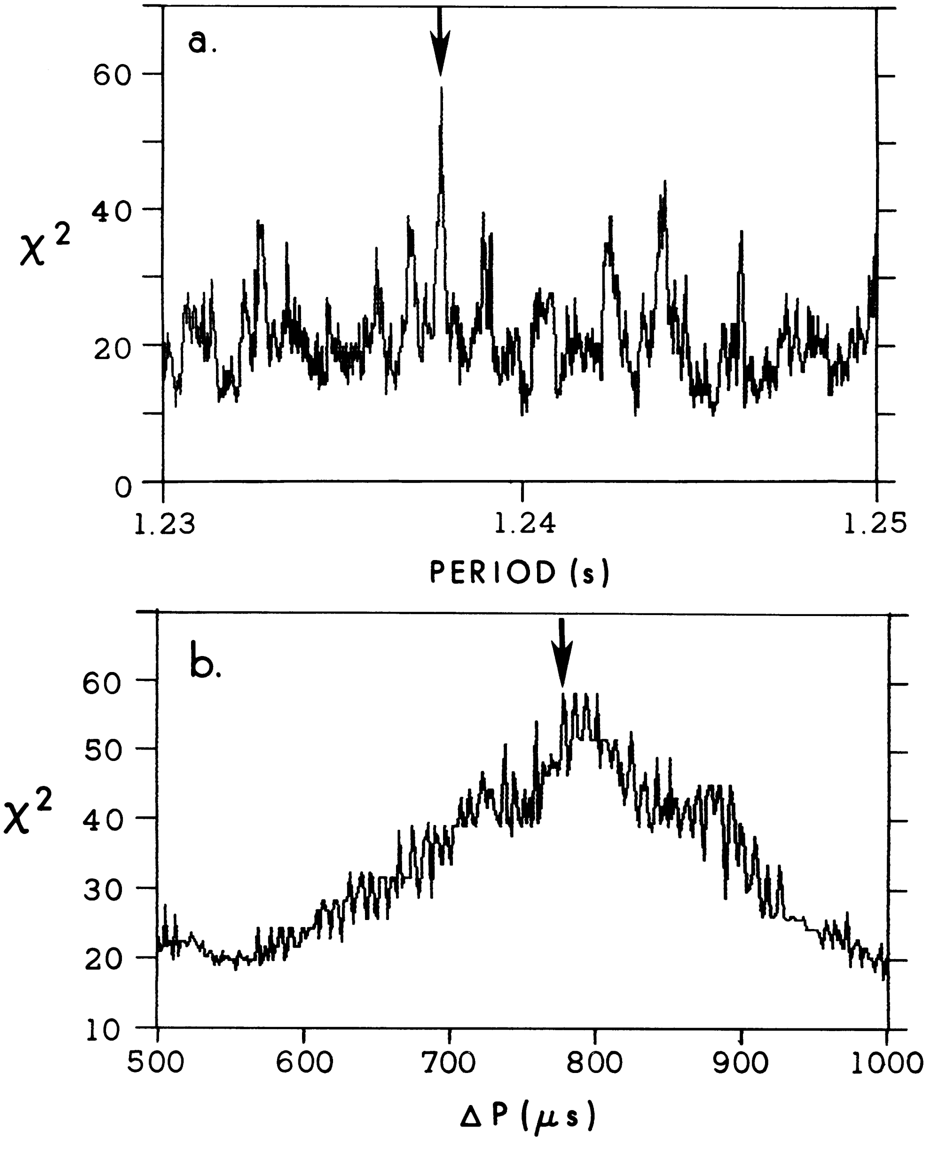

FIG. 2.—The χ^2 dependence on the period used to fold the data is shown. The same showers, bins, and expected background were used as in Fig. 1. (*a*) The period ranges from 1.23 to 1.25 s. (*b*) The period is 1.237 s + ΔP μs. The arrow marks the period obtained from Nagase *et al.*. (1983).

target or converter to produce high-energy γ-rays from energetic protons. The issue of the target will be discussed further below.

The approximate γ-ray flux can be estimated using the signal observed in Figure 1. If we assume the detection area is similar for γ-ray and other cosmic-ray air showers, the γ-ray flux, F, can be estimated by comparing the signal to the cosmic-ray background:

$$F = \left(\frac{S}{B}\right)\Omega I(>E).$$

The flux is given by using the signal to background ratio, S/B, the solid angle of the target region, Ω, and the integral cosmic-ray intensity $I(>E)$. The signal to background ratio is 0.40 ± 0.13. The cosmic ray intensity above 5×10^{14} eV is 5.2×10^{-10} cm^{-2} s^{-1} sr^{-1} (Linsley 1983). The resulting flux is $3.3 \pm 1.1 \times 10^{-12}$ cm^{-2} s^{-1}. This result is for the (apparently sporadic) flux observed in the first part of the 1983 July 11 data. The result is the average flux within the 1.24 s period. The uncertainties given above are statistical, only.

The approximate luminosity in ultra-high energy γ-rays can also be estimated. 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} ergs s^{-1}. This value is close to the total luminosity estimated for the system (Bradt, Doxsey, and Jernigan 1979). Because the source may be sporadic and the γ-rays may be preferentially beamed in our direction, the luminosity (averaged over all times and directions) may be much lower than this. However, the luminosity in charged particles which produce the γ-rays may exceed this value by an unknown factor. In any case, during the times when ultra-high energy γ-ray emission occurs, the particle production process appears to be fairly efficient. That is, the $\geq 10^{15}$ eV charged particles apparently make up a significant fraction of the total luminosity of the entire system.

The charged particles which produced these γ-rays are expected to have energies above 10^{15} eV. Given the relatively long period (1.24 s) of Hercules X-1, such an energy exceeds the maximum energy expected from Hercules X-1 according to certain models of charged particle acceleration by pulsars. The magnetic field in the vicinity of the pulsar surface has been evaluated by Trümper *et al.* (1978) by observing cyclotron resonance emission of X-rays. The result is $(3\text{–}5) \times 10^{12}$ G. Thus, according to the models of Goldreich 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 1985).

The correction of the shower arrival times for the orbital motion of the γ-ray source tacitly assumed that the charged particles which produced the γ-rays were accelerated at the same location at which the X-rays are produced. To check this assumption, the radius of the X-ray source's nearly circular orbit was multiplied by a variable factor, α, and the χ^2 of the resulting light curve was evaluated. The procedure gave $\alpha = 1.03 \pm 0.09$. Similarly, the orbital phase of the source was shifted from the value given by Deeter, Boynton, and Pravdo. The allowed phase shifts were found to be 0.007 ± 0.022 revolutions. The conclusion was that the particle acceleration occurred quite close to the X-ray source or at least was along the line of sight to the source.

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–August, however, Hercules X-1 remained at levels $\leq 5\%$ 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.* (1985) and Delgado, Schmidt, and Thomas (1983) was that the accretion disk may have thickened and blocked the line of sight to 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^0 mesons which decayed to produce the energetic γ-rays discussed in this *Letter*. For such high-energy collisions 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 (Brown and Gould 1970). 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 about three decades lower energy and was not simultaneous with our signal, our result is supportive of their conclusion that multi-TeV γ-rays are produced by Hercules X-1.

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REFERENCES

Boone, J., Cady, R., Cassiday, G. L., Elbert, J. W., Loh, E. C., Sokolsky, P., Steck, D., and Wasserbaech, S. 1984, *Ap.J.*, **285**, 264.
Bradt, H., Doxsey, R., and Jernigan, J. 1979, *X-Ray Astronomy*, ed. W. A. Baily and L. E. Peterson (Oxford: Pergamon), p. 3.
Brown, R. L., and Gould, R. J. 1970, *Phys. Rev.*, **D1**, 2252.
Chanmugam, G., and Brecher, K. 1985, *Nature*, **313**, 767.
Cheng, A. F., and Ruderman, M. A. 1977, *Ap. J.*, **216**, 865.
Deeter, J. E., Boynton, P. E., and Pravdo, S. H. 1981, *Ap. J.*, **247**, 1003.
Delgado, A. J., Schmidt, H. U., and Thomas, H.-C. 1983, *Astr. Ap.*, **127**, L15.

Dowthwaite, J. C., Harrison, A. B., Kirkman, I. W., Macrae, H. J., Orford, K. J., Turver, K. E., and Walmsley, M. S. 1984, *Nature*, **309**, 691.
Goldreich, P., and Julian, W. H. 1969, *Ap. J.*, **157**, 869.
Gunn, J. E., and Ostriker, J. P. 1969, *Phys. Rev. Letters*, **22**, 728.
Kundt, W. 1983, *Ap. Space Sci.*, **90**, 59.
Linsley, J. 1983, *Proc. 18th Internat. Cosmic Ray Conf.*, **12**, 135.
Nagase, F., Sato, N., Makashima, K., Kawai, N., and Mitani, K. 1984, *Proc. Workshop on High Energy Transients, Santa Cruz* (New York: AIP), p. 131.
Parmar, A. N., Pietsch, W., McKechnie, S., White, N. E., Trümper, J., Voges, W., and Barr, P. 1985, *Nature*, **313**, 119.
Trümper, J., Pietsch, W., Reppin, C., Voges, W., Staubert, R., and Kendziorra, E. 1978, *Ap. J.* (*Letters*), **219**, L105.

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