Ultrahigh-Energy Pulsed Emission from Hercules X-1 with Anomalous Air-Shower Muon Production

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A search for bursts of air-shower events from Hercules X-1 at energies above 50 TeV during the calendar period 2 April 1986 to 5 July 1987 yielded two significant bursts, both occurring on UT 24 July 1986. The events during these bursts were pulsed with a period of 1.235 68 s, significantly different from estimates of the contemporaneous x-ray period. The probability that this represents random statistical fluctuations of the background is estimated to be 2×10^{-5}. The muon content of the burst events is anomalous when compared with expectations from γ-ray showers.

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Hercules X-1 is part of a compact binary system located at right ascension (a) 254° and declination (δ) 35.4° consisting of a neutron star and a $\sim 2M_\odot$ companion. It has been studied over a vast range of energies from optical[1] to x rays[2] to very-high-energy[3] (VHE), and ultrahigh-energy[4] (UHE) γ rays. This system displays at least three different periodicities: a pulsar with period 1.2378 s, an orbital period of 1.7 d, and a 35-d periodicity in x-ray intensity. In the latter, the x-ray source appears to be on for about 11 d with a relatively high intensity, off for about 8 d, on for about 8 d with a somewhat lower intensity, and finally off for about 8 d.

Observations of Hercules X-1 by VHE and UHE experiments have shown episodic emission. The first detection[5] at VHE signals consisted of a very strong burst of events lasting about 3 min occurring near the 35-d x-ray turn on; the events were pulsed with a period consistent with the contemporary x-ray pulsar period. Subsequent detections by many groups have observed bursts lasting from a few minutes to a hundred minutes with energies from a few hundred GeV to 500 TeV. In several of these detections,[6,7] the derived pulsar period deviated significantly from the x-ray period. No obvious correlation between the burst times and the binary orbital period has been observed in the VHE detections. On the other hand, a weak correlation exists with the 35-d cycle, most VHE detections having occurred either during the x-ray high states or near transitions between the low and high states. In this Letter, we report results from the CYGNUS experiment on UHE emission from Hercules X-1.

The CYGNUS experiment, described in more detail elsewhere,[8,9] has an air-shower array located around the end station of the LAMPF accelerator in Los Alamos, NM (106.3° W, 35.9° N) at an altitude of about 7000 ft. For the observations reported here, the array consisted of a total of about 50 scintillation counters, each of area 0.83 m^2, deployed over an area of about 10^4 m^2. The spacing and timing accuracy of the counters results in an angular uncertainty in the air-shower direction of about 0.8° for a typical cosmic-ray air-shower event. The trigger requirement gives an effective primary energy threshold of about 50 TeV with an average primary energy for cosmic-ray triggers of about 200 TeV.

The experiment uses the E225 neutrino detector[10] as a muon detector, with an effective area for muon detection of about 44 m^2. The total detector is surrounded by steel and concrete of sufficient thickness to completely suppress the electromagnetic and hadronic components of air showers; a muon must have at least 2 GeV to penetrate the shield.

The method used in our search was motivated by two observations: (1) VHE detections were of relatively short bursts, and (2) all VHE detections contained evidence of a pulsar period. The method chosen was to select days with both a significant excess of events from the source as well as an interval of time which has an excess rate of events from the source, i.e., a possible burst. The events in the burst are then selected, and a period analysis is performed on these events. Our data set contains a total of 340 d with exposure to Hercules X-1 for the calendar time between 2 April 1986 and 5 July 1987.

For each run (day), the on-source number of events was determined with a square bin of 2.3° in δ and 2.8° in a centered on Hercules X-1 a bin size consistent with the angular resolution of the array. The number of off-source events was calculated with bins on each side of the source bin in a. One day, run 171, was by far the most significant found out of the total with 17 events observed on source and 6.0 ± 0.4 expected background, whose Poisson probability is 1.7×10^{-4}. The probability of observing a day with at least this excess in our observing time is then $1.7\times10^{-4}\times340$ (number of days examined) $=0.06$. In this Letter we will concentrate only on this day which was UT 24 July 1986 [Julian day (JD)2446635.5].

In the presence of a well determined uniform background, the bin size which should yield the largest Poisson excess for a Gaussian angular resolution contains only 71% of the signal. Since we will be looking for bursts and periodicity from the source, it is desirable to enlarge the bin size to include a greater fraction of the signal. The final choice was that bin size which optimized the excess number of events in the source bin when compared to the background; this yielded bins of 4.1° in δ by 5° in a giving 46 on-source events over an expected background of 24 events. However, we still use the Poisson probability associated with the original bin size in the overall significance calculation given below.

We have developed an algorithm, using simulated bursts superimposed on the typical time structure of events in a run, to examine the time structure of the on-source events compared with that expected off-source to define the start and stop times of a burst. The algorithm was developed with simulated bursts superimposed on the typical time structure of events in a run. While an algorithm is not required to find strong bursts such as those in run 171, we use the results of the algorithm for consistency with our off-source background studies.

Two distinct bursts are found in run 171, each lasting about 30 min. The first burst, 171A, starts at JD 2446635.53, occurs at zenith angles between about 30° and 40°, and has 7 events over an expected background of 0.53. Burst 171B, starting at JD 2446635.69, occurred near the zenith, and has 10 events with a background of 2.6. These bursts occurred at a 35-d phase[11] of 0.23 and an orbital phase between 0.8 and 0.9.

Each of these bursts was then examined for evidence of a pulsar periodicity with the Protheroe statistic.[12] A period sweep over a range $\pm0.3\%$ in period (1.23378 to 1.24178 s) about the x-ray period was made with the appropriately barycentered times of each event. This period range was chosen to allow deviations from the x-ray pulsar period similar to those previously reported by VHE γ-ray experiments.[6,7] The period with the maximum power in burst 171A (171B) is 1.23572 ± 0.0004 s (1.23575 ± 0.0003 s). When the two bursts are combined coherently, the maximum power is at the period 1.23568 s. The period sweep for the combined data sets (171A and 171B) is shown in Fig. 1 along with a circular phase distribution of the events at that period. To examine the data for evidence of other periodicities, period sweeps were made over a vast range of periods from 0.9 to 1.5 s, and the power observed at this period is the maximum over the entire range.

The technique used to determine the significance of

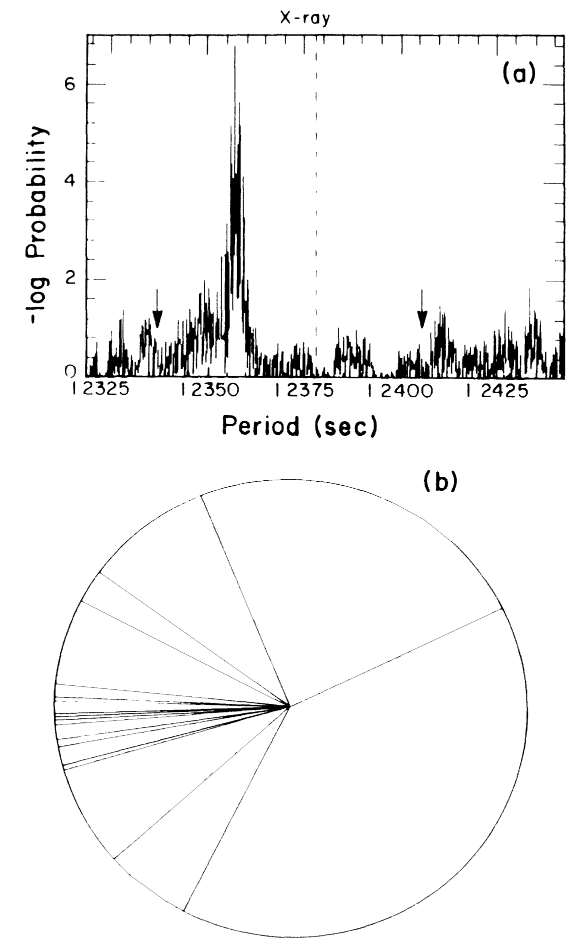

FIG. 1. (a) The period sweep for the combined bursts; the period window actually used is denoted by the arrows in the figure. (b) A phaseogram of the events at the period found in the combined sweep. Since there is an arbitrary phase origin in this figure, a phase scale is not given.

these bursts combines the separate probabilities in a straightforward manner. The pretrial probability that the power at 1.23568 s is a result of a statistical fluctuation is 3×10^{-7}. As determined by Monte Carlo simulations, this probability must be multiplied by a factor of 380 to account for the trials associated with the period sweep (i.e., oversampling, period window) and an additional factor of 3 to account for combining the two separate bursts into one. Then, the probability that this power is a fluctuation is 3.3×10^{-4}. Since this probability is independent of the probability of observing the excess in the run, an overall estimate of the change that this observation is a fluctuation of the background is $P_{171}=0.06\times3.3\times10^{-4}=2\times10^{-5}$.

We have examined our off-source data to verify the statistical properties of our data. Each of the six nearest off-source bins was treated in the same way as the on-source bin for every run. The result was that no off-

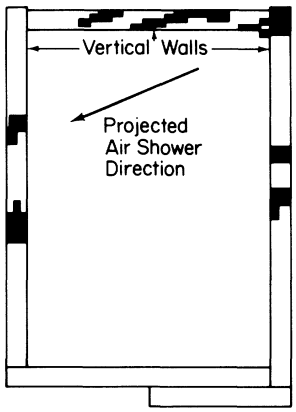

FIG. 2. The response of E225 multiwire proportional chambers for a sample in-phase burst event. The detector is viewed from above showing the vertical walls. Each multiwire-proportional-chamber hit is shown as a black square. The projected air-shower direction is also shown.

source region showed any evidence for a systematic effect that could have caused these bursts or their observed periodicity.

Given the very large signal-to-background ratio (17 events when 3 were expected) during the bursts, they represent a very pure sample of events with which to study the characteristics of the showers on an event-by-event basis. Specifically, the number of muons observed in each event, as unambiguously determined from the muon detector, can be compared with expectations from γ and hadron showers. We consider only those events within ± 0.03 of the main phase peak in order to enhance the sample signal-to-noise ratio still further. Figure 2 shows the muon detector for one of these events. Table I summarizes the number of muons observed in each of the burst events along with the number of muons expected for similar cosmic-ray background events. For each burst event, the expectation was calculated with observed cosmic-ray events having nearly the same zenith angle, shower size, and core location as the burst event. The burst events have a large number of muons associated with them, especially when compared with that expected from standard γ-ray showers, which is at least an order of magnitude less than that expected from hadronic showers.[13] The table shows that on the average the muon content of the burst events exceeds that expected from the hadronic background events.

Furthermore, we have reconstructed the shower size of each of the burst events and compared their shower sizes with the shower-size distribution of hadronic background events coming from the same zenith angle range.[8] The shower size of burst events tends to be larger than that of the background. This is expected if the source spectrum is flatter than the cosmic-ray spectrum. There is about a $\sim 3\%$ probability that the observed spectrum could have been a fluctuation of the background spectrum to such

TABLE I. Characteristics of showers observed in phase during bursts 171A and 171B. The time of each event is given in seconds UTC (coordinated universal time) on JD 2446635.5. The zenith angle of the event is ϑ_z, the distance of the core from the muon counter is R_μ, N_e is the reconstructed shower size, and E_0^p is the primary energy, with the assumption of the primary to be a proton. N_μ^{obs} is the number of muons observed in the event while $\langle N_\mu^{\text{bg}} \rangle$ and N_μ^{bg} are the mean and median number of muons observed in similar background cosmic-ray events. Typical errors in each of the parameters are $\delta R_\mu \cong 4$ m, $\delta N_e \cong 20\%$, and $\delta E_0^p \cong +100\% - -50\%$.

UTC (s)	ϑ_z (deg)	R_μ (m)	N_e (10^4)	E_0^p (TeV)	N_μ^{obs}	$\langle N_\mu^{\text{bg}} \rangle$	N_μ^{bg}
2920.988	37.6	36	10	480	9	4.3	3.4
3790.129	34.7	36	6	280	5	2.0	1.2
4005.211	34.7	21	19	780	10	5.0	4.0
4330.355	34.5	13	12	540	7	5.6	4.4
4486.180	32.9	11	7	320	8	4.0	2.5
4608.578	33.7	45	13	570	4	3.0	2.4
16417.531	6.9	1.6	3	100	>12	4.1	3.3
17419.969	12.0	47	23	850	0	2.7	1.6
17482.938	11.4	63	43	1580	0	3.6	2.3
17610.305	12.2	23	6	205	1	1.8	1.0
17683.188	11.0	46	70	2590	6	4.4	3.8

high energies. If the spectrum of these burst events is indeed flatter than the background, then the energy of these events may be larger than background events of the same shower size; it may then be possible to explain the apparent excess of muons in the signal over background hadronic showers, but will not explain the excess over that expected from γ-ray showers.

Because the source spectrum is unknown, the flux particles arriving from the source can only be estimated. An examination of Table I shows that all of the events in the burst are well above the array threshold. The effective area of the array for these primary energies, as determined by Monte Carlo simulations, is about 2×10^4 m^2. There was an excess of 14 events observed in the bursts during a time of about 1 h which yields an estimated burst flux of $\sim 2\times10^{-11}$ cm^{-2} s^{-1}. A mass limit on the particle initiating the showers can be computed from the 0.07-s phase dispersion and the 100-TeV minimum energy of the events as well as the distance to the source (5 kpc); the result is that the mass must be <60 MeV/c^2.

There have been two other independently reported detections of Hercules X-1 at roughly the same time as ours in VHE γ rays. Lamb *et al.*[6] have reported a detection on 11 June 1986 and Resvanis *et al.*[7] have reported a detection on 13 May 1986. Both of these detections showed evidence of the same pulsar period (1.23579 ± 0.0002, and 1.23593 ± 0.0002, respectively) as that observed in run 171. Our overall statistical significance contains the appropriate trials factor for scanning the entire width of the chosen period window and is therefore independent of the remarkable agreement with the period observed by these other experiments.

In summary, we have observed two bursts of events from Hercules X-1 on UT 24 July 1986. These bursts have a probability of occurring from random background fluctuations estimated to be approximately 2×10^{-5}. Extensive searches of the background have not revealed any other burst or combination of bursts as unlikely as those observed on run 171. The period observed in the bursts is 1.23568 s, significantly different from the x-ray period. This period is consistent with that derived from two independent observations of Hercules X-1 made within roughly two months of our observations. It is also the first observation of a pulsar period made by an extensive-air-shower array. This observation of UHE signals with a period significantly different from the x-ray period is suggestive of different emission regions for UHE radiation and x rays. Finally, an analysis of the shower characteristics of these events shows a larger shower size as compared with the background as well as a slight excess of muons when compared with similar hadronic background showers. On an event-by-event basis, the number of muons observed in the burst events is at least an order of magnitude larger than that expected from standard γ rays.

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