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Ultra-High Energy Signals from Hercules X-1

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ABSTRACT

The expectation that high energy neutrinos are emitted from astrophysical objects depends strongly on the observation of those objects in gamma-rays, especially at TeV and PeV energies. A search for bursts of gamma ray events from Hercules X-1 at energies above 50 TeV yielded two significant bursts, both occurring on UT 24 July 1986. The events were pulsed with a period of 1.23568 s, significantly different from estimates of the pulsar period at that time. The probability that the signal is a random background fluctuation is about 2×10^{-5}, not including the fact that there were two other independent observations of the source at nearly the same time. The muon content of the burst events is anomalous when compared with expectations of gamma ray showers, perhaps signalling the onset of new physics at these energies.

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Identification of an astrophysical point source depends on several properties of the primary particle: it must be chargeless, relatively light, and relatively long lived. Of the known particles, only the photon, neutrino, and neutron satisfy these requirements; of these, the neutron can usually be eliminated because of its moderate mass and lifetime leaving only the photon and neutrino as candidates for detection. At low energies ($\sim$ TeV), the emission of photons from a point source could be due to acceleration and radiation by electrons. On the other hand, it is commonly believed that it is only possible to accelerate hadrons to higher energies. The hadrons then interact with the surrounding material to produce π^0's. Copious production of neutrinos must then result from the decay of the $\pi^\pm$ produced in this astronomical beam dump. It is partly for this reason that UHE ($\sim$ 100 TeV) gamma ray astronomy is strongly linked with high-energy neutrino astronomy. Besides the inherent astrophysical interest, UHE gamma ray astronomy might solve the mystery behind the origin of the cosmic rays. In addition, study of the characteristics of the showers produced in the atmosphere caused by the primaries from such a source is perhaps providing hints of new physics at energies not available to terrestrial accelerators. Herein is reported results from the CYGNUS experiment on UHE emission from Hercules X-1, including evidence for the anomalous production of muons in the air showers from the source.

Her X-1 is part of a well studied compact binary system thought to consist of a neutron star and a $\sim 2M_\odot$ companion. It has been observed over a vast range of energies from optical[1] to x rays[2] to very high energy[3] (VHE, $\sim$ 1 TeV) and ultra high energy[4] gamma rays. The system displays at least three different periodicities: a pulsar with period 1.2378 s, an orbital period of 1.7003 d, and a 35 d periodicity in x ray intensity. Observations of Her X-1 by VHE and UHE experiments have shown very episodic emission. The first detection consisted of a very strong burst of events, lasting about 3 minutes, and pulsed with a period consistent with the x ray pulsar period. Subsequent detections by many groups have been made of bursts lasting from a few minutes to a few hundred minutes. In one of these detections[5], by far the most significant VHE detection ever made, the flux was observed to increase to, and then decrease from, $\sim$ 50% of the background cosmic ray flux over a period of about 50 minutes. All detections have shown evidence of the pulsar period; in several of these observations[6][7], the derived pulsar period deviated significantly from the x ray period.

The CYGNUS experiment[8] is an air shower array located around the end station of the LAMPF accelerator in Los Alamos, NM (107.6°W, 35.9°N) at an altitude of about 7000', corresponding to an overburden of 800 g/cm^2 of atmosphere. For the data considered here, there were 60 counters, deployed over an area of $\sim 10^4 m^2$, each of 83 m^2 area. 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. There are currently 96 counters deployed over an area of $\sim 2\times10^4 m^2$, an additional 96 counters are being deployed in summer-fall 1988 over an area of $\sim 6\times10^4 m^2$.

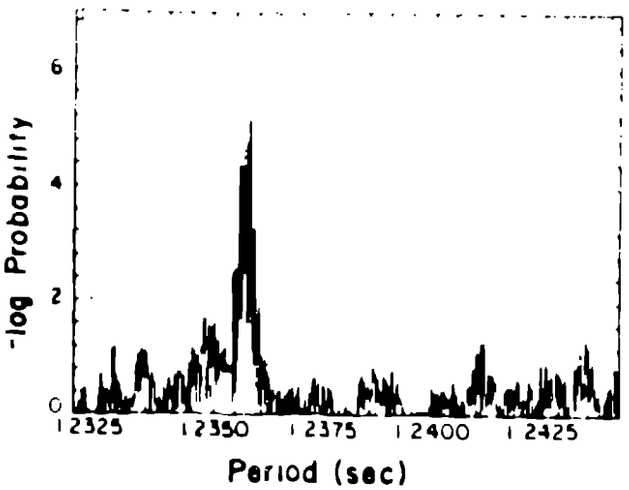

Figure 1: Period sweep around the pulsar period for the combined bursts.

Our data set contains a total of 340 days with exposure to Her X-1 starting from April 2, 1986 until July 5, 1987. The method used in our search[8] 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 with a significant excess rate of events from the source, i.e. a possible burst. The events in the burst are then extracted and a period analysis is performed on the events.

When all of the days with exposure to Her X-1 are examined, one day, run 171, was found to be by far the most significant. The total probability, including the fact that 340 days were searched, for observing the excess events from the source is 0.06.

Based on Monte Carlo simulations of bursts superimposed on the typical time structure of events, an algorithm was developed to help determine the burst events within a run; this algorithm, though not required to find bursts as strong as those found in run 171, was developed to allow study of the background. When this algorithm is applied to run 171, two distinct bursts are found, each lasting about 30 minutes. The first burst, 171A, started at JD 2446635.53, occurred at zenith angles between about 30° and 40°, and had 7 events over a background of .53. Burst 171B started near the zenith about 3.8 hours later, and had 10 events over a background of 2.6.

Finally, after the bursts are defined, a period analysis is performed to search for evidence of a pulsar periodicity. A period sweep over a range ±0.3% in period (1.23378 sec. to 1.24178 sec.) centered on the x-ray frequency was made and is shown in Figure 1. The maximum power is at the period 1.23568 sec., a circular phase distribution of the events at that period is shown in Figure 2. To examine the data for evidence of other periodicities, including possible systematics, period

Figure 2. Circular phaseogram of the events at the period shown in Figure 1; since there is an arbitrary phase origin in this figure, a phase scale is not given.

sweeps were made over a vast range of periods from .9 sec to 1.5 sec, and the power observed at this period is the maximum over the entire range.

The probability that these bursts are due to a random fluctuation of the normal background is simply estimated. As previously mentioned, for any run the probability that the background has fluctuated to give at least as many excess events as that found in run 171 is 0.06. Additionally, the pre trial probability that the power at 1.23568 sec is due to a fluctuation in the phase distribution is 3×10^{-3}; as determined by Monte Carlo simulation, this must be multiplied by a factor of 1/10 to account for the trials associated with the period sweep (i.e. oversampling, period window, combining bursts) resulting in a post trial probability of 3.3×10^{-4}. The combined probability that this result is due to a chance fluctuation of the background is then

$$P_{171} = 0.06 \times 3.3\times10^{-4} = 2\times10^{-5}.$$

There are several possible systematic effects that could perhaps result in observations similar to these. To eliminate this possibility, for every run each of the nearest six off source regions was examined as if it were the on source region. No evidence of any systematic was found that could have caused either an excess of events, an excess rate of events, or periodicity, in any of the data.

Similar signals were also observed by two independent VHE experiments at nearly the same time as these bursts; the Whipple collaboration[6] reported a detection on June 11, 1986 and the Haleakala collaboration[7] reported a detection on May 13, 1986. Both of these detections showed evidence of the same pulsar period (1.23579 ± .0002 s, and 1.23593 ± .0002 s, respectively) as that observed on run 171. These contemporaneous detections, while not included in the overall

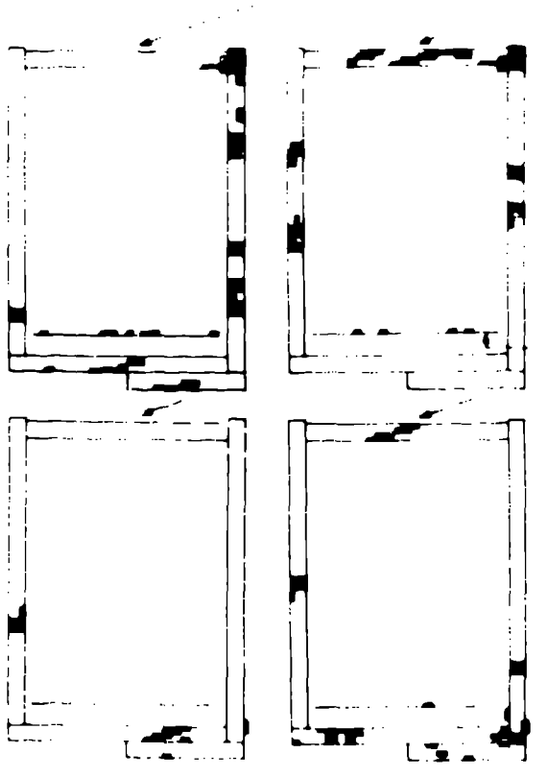

Figure 3: A sample of four of the burst events as observed in the E225 MWPC's. The roughly cubical detector is shown looking down from above; each MWPC hit is represented by a small black square. The arrows represent the projected shower direction for the event.

significance of this result, will shed some light on the production mechanism at the source.

Since every indication is that this signal is genuine, there are several consequences than can be explored. For example, the very large signal to background during the bursts implies that they represent a very pure sample of events to study the characteristics of the showers on an event by event basis. Further, since a good estimate of the signal events are only those in phase, only those events within $\pm .03$ of the main phase peak will be examined. Specifically, the number of muons observed can be compared with expectations from gamma and hadron showers. Figure 3 shows some of the events from burst 171A in the muon detector; clearly, the muons are coming from the same projected direction as the air shower. A summary of the number of muons observed in each burst event, along with the number expected from similar cosmic ray background events, is given in Table 1. 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[9].

The shower size of each burst event has been reconstructed[8] and compared

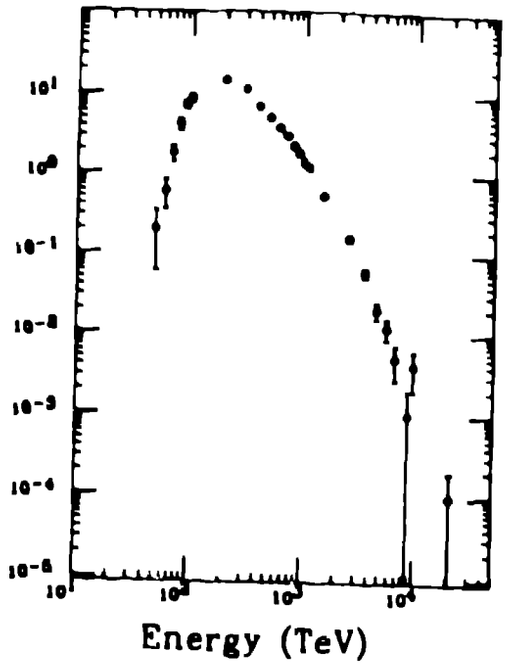

Figure 4: Energy spectrum of background cosmic ray events as observed in the CYGNUS array. The vertical scale is arbitrarily normalized. The observed spectrum falls at low energies due to trigger inefficiencies and at high energies because of the fall in the cosmic ray spectrum.

with the shower size distribution of background events. As illustrated in Table 1 and Figure 4, the shower size of the burst events tends to be larger than the background, as expected if the source spectrum is flatter than the cosmic ray spectrum.

The source spectrum being unknown implies that the flux of particles arriving from Her X 1 can only be estimated. Since all of the burst events are well above the array threshold, the effective area of the array at these energies, based on Monte Carlo simulations, is about $2\times10^4 m^2$. There was an excess of 14 events observed in the bursts during about 1 hour which yields a burst flux, $\mathcal{F}$, of 2×10^{-11} cm^{-2} s^{-1}. The luminosity, $\mathcal{L}$, can be estimated since the distance to Her X 1 is about 5 kpc and the mean energy of the events is about 750 TeV; then $\mathcal{L}$ is estimated as $\mathcal{L} = 4\pi R^2 \mathcal{F} \cdot E \approx 7\times10^{37}$ erg s^{-1}. For comparison, this is about 20,000 times the solar luminosity but only about 10^{-15} times the neutrino luminosity of SN1987A; it is also slightly less than the Eddington luminosity, $\mathcal{L}_{Ed} = 1.8\times10^{38}$ erg s^{-1}.

Further, a limit on the mass of the particle can be placed since the primaries maintain time coherence over a very long time interval. Table 1 shows that the minimum energy is about 100 TeV and the largest energy is several times the minimum. Making the usual approximations it is easy to find that the time dispersion between two particles of mass M and energies $E_1 \cdot E_2$ is

$$\Delta t \simeq \mathcal{M}^2 d/2c \cdot [1/E_1^2 - 1/E_2^2]$$

For E_2 only several times E_1, the limit on $\mathcal{M}$ becomes

$$\mathcal{M}[GeV] \sim 4.4\times10^{-3}\,\Delta t^{1/2}[sec]\,E_1[TeV]/d^{1/2}[kpc]$$

which works out to be a limit of $\mathcal{M} \sim 60$ MeV/c^2 for Her X-1 assuming Δt of 0.1 seconds.

Finally, the fact that the pulsar period of the VHE-UHE signals that was observed during the bursts is significantly different than the x-ray period strongly suggests that the emission region of the VHE-UHE radiation is different than that for x-rays.

In summary, two bursts of events from Hercules X-1 have been observed on UT 24 July 1986 by the CYGNUS experiment. These bursts are not caused by any systematic effect in the experiment and have a probability of occurring from random background fluctuations estimated to be less than 2×10^{-5}. The period observed is 1.23568 seconds, significantly different than the x-ray period but consistent with two independent observations at nearly the same time. Finally, an analysis of the shower characteristics of the events shows a larger shower size as well as a slight excess of muons when compared with similar hadronic background events. 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 gamma rays.

Some concluding remarks are in order. The implications of these observations for both particle physics and astrophysics may be enormous. The anomalous muon content of the showers may reflect the onset of new particle physics in photon-nucleon interactions at center of mass energies $\sim$ 1 TeV. The observation of such high energy particles with a periodicity shifted from the pulsar's period is difficult to explain. These implications require that these observations be confirmed by further observations of this and other sources. Many of the traditional roots of particle physics are found in the study of cosmic rays- these observations may begin a return to those roots.

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Table 1. Characteristics of showers observed in phase during bursts 171 A and B. The time of each event is given in seconds UTC 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 assuming the primary to be a proton. N_μ^{obs} is the number of muons observed in the event while $< N_\mu^{bg} >$ 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: $\delta R_\mu \simeq 4$ m; $\delta N_e \simeq 20\%$; and $\delta E_0^p \simeq +100\%/-50\%$.

UTC (Sec)	θ_z (°)	R_μ (10^4)	N_e (TeV)	E_0^p	N_μ^{obs}	$< N_\mu^{bg} >$	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	32.8	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