SEARCH FOR POINT SOURCES OF U.H.E. GAMMA RAYS USING THE UTAH CHERENKOV ARRAY

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Abstract

An array of 4 Cherenkov telescopes has been used to obtain directions of 100 Ted' showers by the fast timing technique. The Crab Nebula, Hercules X -1, and Cygnus Y-3 have been observed by this array during 198$-1990. The muon sizes of the showers have also been determined by the Michigan Muon Array, which surrounds the Cherenkov array. Flux limits are presented for emission of muon-poor showers from these sources. In addition, limits are presented for emission within phase intervals near 0.3 and 0.7 for muon-poor and all showers from Cygnus X-3. No signals were detected in these observations.

Introduction There have been numerous reports of U.H.E. emissions from Cygnus X-3, the Crab Nebula, and Hercules X-1. The use of a 4 telescope Cherenkov array and an extremely large area muon detector array at Dugway, Utah results in a very sensitive system for the detection of point-source, muon-poor signals in showers above 100 TeV. Simulations imply that the telescope array has good energy resolution (~20%) and the muon content of hadronic showers is expected to be highly correlated with the shower energy. Consequently the rejection of hadronic showers by selecting muon-poor showers should be very efficient.

Apparatus and procedures The field of view of each telescope is 2.9°. Within this field of view, fast timing is used to select showers from within 1° of the direction of the potential source which is tracked by the telescopes. The requirement of muon-poor showers, done for most of the limits reported below, is based on the assumption that the showers are produced by gamma rays and are poor in muons as is expected.' This assumption must be stated because some of the detections of these sources have indicated that the signals are not muon-poor or are only weakly muon-poor.[2-4]

The Cherenkov telescope array was described in the Adelaide ICRC proceedings[5] and earlier results from this array were reported in those proceedings for Cygnus X-3[6] and Hercules X-1.[7] This is the first report of results of the use of the telescope array together with the University of Michigan muon array. The telescopes are located at the corners of a 170 m square.

The telescopes have 36 cm diameter mirrors and a single photomultiplier tube in the focal plane. Events are accepted when at least 3 telescopes trigger on a shower. The pulse amplitudes are used to obtain the approximate core location aid the shower energy. Showers are accepted only when the core location is located within a 120 m radius circle which passes through the telescopes, giving a sensitive area of 45,000 m^2. The pulse timing is used to obtain the shower direction and arrival time. The simulations show the t accepting showers within a 1° radius region centered on a potential source is nearly optimal for maximizing the signal to background ratio. The telescopes are operated on clear, moonless nights by the operators of Fly's Eye 2. "The telescope array has triggering rates of about 5 showers per minute. With an energy cut of 100 TeV, the background event rate within 1° of a potential source is about one shower in 6 minutes.

The muon detectors have been described in detail elsewhere.[8] The array has been operated with the Utah Air Shower Array[9] and CASA[10] as well as with the telescope array. The muon array consists of scintillation counters buried under about 3 m of earth. The "punch through" of particles other than muons has been discussed[9] and it was concluded that a negligible fraction of gamma rays are misidentified as not muon-poor Sue to this effect. During the time in which most of the data reported in this paper was collect :d, there were 8 banks of muon detectors in operation, with a total muon area of 1280 m^2. All 3 banks are located within the 120 m radius circle on which the telescopes are located. During t he interval in which data reported here was taken in 1988, the muon array consisted at first of a banks and later of 6 banks. At present, the array has been expanded to 16 banks.

A lateral distribution due to Greisen[11]is fitted to the muon data for each event to get the muon size. It is given by $\rho_{ì}(x)$ á $N_{ì}x^{-0.75}(1 + x)^{-2.5}$ where ρ, is the muon density, $N_{ì}$ is the muon size, and x r / r_0 with the parameter r_0 = 300m. Muons are accepted within a narrow window on each side of the shower arrival time determined by the telescopes. For 100 TeV showers the typical number of accepted muon; is about 10 . The fitted number of muons is found to be roughly proportional to the shower energy. Showers are accepted within 40° of the zenith. Within this angular range the observed zenith angle dependence is fitted by $\cos^n\theta$, with n near 3. This strong dependence is at least partly due to projection effects and the greater effective shielding thickness for non-vertical showers An energy cut at 100 TeV is applied to the data in which the muon-poor selection is done. A shower is considered to be muon-poor if the muon size is less than 10% of the (energy and zenith angle dependent) mean muon size or if the number of muons is 0 or 1. In the 1989 and 1990 data, this cut rejects about 99% of the showers.

The flux limits given below are obtained by dividing the maximum number of signal events (at the 90% confidence level) by the effective area of the telescope array and the running time, and correcting for the triggering and reconstruction efficiencies. For the muon-poor shower limits a correction is also made for the efficiency of accepting gamma ray showers.

Results and discussion Table 1 gives upper limit tuxes in yearly intervals for the three sources. The threshold energy is 100 TeV and only muon-poor showers are accepted. A relatively high threshold is used so that the cosmic ray showers will be rejected very efficiently in the selection of muon-poor showers. Since the Crab Nebula was c bserved in seasons overlapping boundaries of years, the year of observation is listed, for example, as '88-'89 for the season including the months from October 1988 to February 1989. No background j subtraction is attempted. That is, the 90% confidence level upper limit is based on the flux calculated assuming the muon-poor showers are all part of a signal.

Source	Year	Observed Showers	Running Time (hours)	Flux Upper Limit ($cm^{-2}\ s^{-1}$)
Crab Nebula	'88-'89	10	80	2.4×10^{-13}
	‘89-‘90	4	42	2.2×10^{-13}
	late '90	4	40	2.4×10^{-13}
Hercules X-1	1989	19	67	4.5×10^{-13}
	1990	1	59	7.9×10^{-14}
Cygnus X-3	1988	61	136	6.3×10^{-13}
	1989	19	142	2.1×10^{-13}
	1990	5	90	1.3×10^{-13}

Table 1: Annual flux limits for muon-poor showers with E   100 TeV.

In Table 2, the muon-poor requirement is applied to the Cygnus X-3 data in specified phase intervals using the cubic ephemeris of van der Klis and Bonnet-Bidaud[l2]. The flux upper limit is averaged over the phase interval 0-1, as is usually done with results from Cygnus X-3. The two phase intervals were chosen to include the regions in which periodic effects have usually been reported. Very low limits are obtained for 1989 and 1990.

Year	Phase	Observed Showers	Running Time (hours)	Flux Upper Limit ($cm^{-2}\ s^{-1}$)
1988	0.15-0.4	22	39	2.3×10^{-13}
	0.55-0.8	12	26	2.0×10^{-13}
1989	0.15-0.4	5	29	1.0×10^{-13}
	0.55-0.8	3	36	5.7×10^{-14}
1990	0.15-0.4	1	21	5.6×10^{-14}
	0.55-0.8	0	21	4.2×10^{-14}

Table 2: Cygnus X-3 flux limits for muon-poor showers
within specified 4.8 hour phases.

Flux limits are given in Table 3 for Cyg)C-3 in two phase intervals, without the muon-poor requirement. Lower energy thresholds are used than were used in the case for muon-poor showers. For 1989 and 1990 data the threshold was 40 TeV. A higher (70 TeV) threshold was selected for the 1988 data because a higher triggering level was in effect at that time.

Year	Phase	Observed Showers	Expected Showers	Excess (ó)	Flux Upper Limit ($cm^{-2}s^{-1}$)
1988	0.15-0.4	473	503.4	-0.9	1.2×10^{-13}
	0.55-0.8	316	354.5	-1.5	1.2×10^{-13}
1989	0.15-0.4	524	522.3	0.1	2.7×10^{-13}
	0.55-0.8	624	630.6	-0.2	2.0×10^{-13}
1990	0.15-0.4	214	219.2	-0.2	2.1×10^{-13}
	0.55-0.8	240	207.9	1.6	4.9×10^{-13}

Table 3: Cygnus X-3 flux limits in specified 4.8 hour phases
without selecting muon-poor showers

Unlike the cases where muon-poor showers were selected, the number of background showers was calculated for Table 3 using a method based on measuring the ratio of the number of showers within 1° of the target to the number in an outer annulus between 1.5° and 2.5° from the target. For a fixed threshold, this ratio has negligible dependence on zenith angle for zenith angles less than 40°. The background in a phase interval is then calculated using the inner circle/outer annulus ratio in other phase intervals and multiplying this ratio by the number of showers in the outer annulus for the phase interval of interest. This method gives the expected numbers of showers shown in Table 3. In this case, the excess in the inner ring can be expressed as a standard deviation and this is given in the table. The standard deviations were calculated following Li and Ma.[13] The running times can be found in Table 2 and were not repeated in Table 3. No signals were detected. Flux limits are given in the last column. For 1989 and 1990 these limits are higher than those given in Table 2. However, these limits are not based on the muon-poor requirement so they apply to a wider range of models.

In addition to the limits described above, the data were checked for significant excesses on time scales of a month, a day, and a half hour. No statistically significant signals were found.

There has been a recent TeV detection of the Crab Nebula with a significance of 20 standard deviations.[14] The differential spectrum between 0.4 and 4 TeV was found to be $2.5 \times 10^{-10}(E / 0.4\mathrm{TeV})^{2\ 4 \pm 0.3}\ \mathrm{cm}^{-2}\mathrm{s}^{-1}$ TeV-1. If the spectrum is extrapolated to 100 TeV using 2.4 as the spectral index the flux above 100 TeV is $3.1 \times 10^{-14}\mathrm{cm}^{-2}\mathrm{s}^{-1}$. The limits for the Crab given in Table 1 do not contradict such an extrapolated flux. The sensitive limits for Cygnus X-3 do impinge upon the earlier estimates for the spectrum from that object, however.

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