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Astronomy at Ultra-High Energies: Results from the CYGNUS Experiment

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The CYGNUS Collaboration

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ABSTRACT

The CYGNUS experiment is composed of an air-shower array and muon detectors, located in Los Alamos, NM, and operating at energies above about 50 TeV. Recent results include a search for emission from Cygnus X-3 during the radio outbursts of June and July, 1989, preliminary results from a search for diffuse emission from the galactic plane, and preliminary results from a search for emission from possible northern hemisphere point sources, both known and unknown.

The interest in ultra-high energy astronomy has blossomed in the last several years: there is now at least one experiment on nearly every continent in the world. Further, the motivation for these efforts is twofold: an intense interest in the astrophysical mechanisms capable of generating particles of such high energies, and in the particle physics that can be uniquely explored at these energies. It is with these motivations that the CYGNUS collaboration is exploring this unique field.

The salient features of the CYGNUS experiment, which has operated nearly continuously since April, 1986, will be highlighted here; further discussions of the properties of the experiment, as well as previous results, can be found in ref. [1]. The experiment is located at an altitude of 2,130 m, corresponding to an atmospheric overburden of 800 g/cm^2, in Los Alamos, NM (106.3°W, 35.9°N). The air-shower array is composed of 106 scintillation counters, each counter having an area of about 1 m^2, deployed over an area of about 20,000 m^2; there is typically 15 m between counters. The direction of each event, determined from the timing information from each counter, is reconstructed with a typical uncertainty of 0.8°; the maximum systematic error in directional reconstruction is determined to be less than 0.3°, small enough to be of no practical concern. No requirement is made on the core

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position of the events. The experiment has a roughly cubical muon detector, 6 m on a side, that presents an effective area of about 44 m^2 to a typical air shower event; a muon must have a minimum energy of about 2 GeV to penetrate the shielding around the muon detector.

During the week of 30 June, 1989, a layer of lead, about one radiation length thick, was placed above each detector. The lead produces a lower trigger threshold and a larger effective area (area over which triggers are recorded) of the array by converting some of the photons in the shower. This results in both a change in data collection rate (about twice the event rate) and a change in the average number of detected muons per event. The number of detected muons per event decreased from typically 2.0 to 1.65 after the lead was installed.

More recently, an additional 96 counters have been deployed over an area of about 60,000 m^2. The spacing between the new counters varies from 20 m for the region nearest the original array to 30 m for the region furthest from the original array. The reason for the graded approach is to expand the high-energy capabilities of the CYGNUS experiment in a smooth fashion. This expanded array has a sensitivity to point sources about a factor of 2 to 4 times larger than the original array. An additional muon detector, composed of 30 scintillation counters of total area 70 m^2, is buried near the center of the new array under an overburden of about 710 g/cm^2, corresponding to a muon energy threshold of about 1.5 GeV. Finally, the anticoincidence shield from another neutrino detector, LAMPF experiment 645, is soon to be added to the data collection system, providing an additional 80 m^2 of muon detection near the center of the old array.

A powerful check of the absolute pointing accuracy and angular resolution of the array can be made by observing the deficit of cosmic rays from the direction of the sun and moon. Since cosmic rays of these energies are not effected by the solar or terrestrial magnetic fields, the shadowing caused by absorption on the sun and moon should be observable as a deficit around these objects, which each are about 0.25° across. A search for the sun and moon shadow produces a combined 4σ deficit from a total of over 200,000 events within 5° of the sun and moon, consistent with the number of cosmic ray events and the size of the objects. A maximum likelihood analysis of the deficit yields an average angular resolution of 0.8°. This is the first time the shadows of the sun and moon have been observed and used to establish the angular resolution of an air shower array.

In 1989, Cygnus X-3 had two large radio outbursts, the first began on about 2 June and the second on 21 July. In fact, Cygnus X-3 was first discovered as a γ-ray source at energies above $\sim$ 1 TeV in observations made about one week after the first observation of a large radio outburst in September, 1972. Several groups reported signals at both $\sim$ 1 TeV and $\geq$ 100 TeV energies[2] during the last such outburst of October, 1985. Most of these reports were of emission, lasting from minutes to days, during the first several days after the outburst; other experiments reported possible excesses lasting approximately one month around the time of the radio flare.

The data are analyzed on a day-by-day basis, each day defined to be the time from which Cygnus X-3 rises until it sets in the sky. The signal region is chosen to maximize the significance of a point-source signal; the total bin width is 2.3° in declination by 3.0° in right ascension and should contain 71% of the total signal. The daily background is estimated from the average of 5 background bins on each side of the source bin in right ascension

This simple technique accounts for daily variations in the operating characteristics of the array from, for example, changes in the local air pressure. An appropriate cut in hour angle is made to ensure equal exposure for the source and background bins.

It is expected that showers initiated by γ-ray primaries should be deficient in muons when compared with proton primaries; a cut requiring muon deficient events should thus enhance the sensitivity to γ-ray point sources. Nevertheless, evidence exists to the contrary.[1] Thus, all observed events were analyzed; events with no detected muons were considered separately. This second set of data is a subset of the first so that the results from the two analyses are not independent.

The calculation of the effective area, needed to calculate all of the fluxes given here, is based partially on the observed cosmic ray rate and partially on a Monte Carlo calculation of the acceptance of the array. The motivation for this is to make the fluxes less prone to errors in the Monte Carlo simulation due to, for example, uncertainties in the exact trigger condition for the array. For each data set, the effective area for cosmic ray showers is simply calculated using the known cosmic ray flux and the observed number of background events. A Monte Carlo calculation is used to correct for the change in array response due to the different energy spectra for background and source events, and due to the different longitudinal development of photon and hadron induced showers. This increases in the effective area by a factor of 3.0, mostly due to the assumed hard spectrum, for the data considered here. The Monte Carlo calculation predicts the absolute cosmic ray trigger rate of the array to within $\pm$ 50% for a variety of different trigger conditions.

The daily excess number of events is shown in Figure 1; occasional gaps, the most notable of which was the day of the first burst, are due to experimental hardware failures. Taken together, there were 4347 events in the source region with 4338 ± 21 expected background (2255 observed and 2254 ± 15 expected for events with no detected muons). A 90% confidence level (CL) upper limit on the flux from Cygnus X-3 during this time is $3.0 \times 10^{-13} cm^{-2} s^{-1}$ for all data ($2.2 \times 10^{-13} cm^{-2} s^{-1}$ for data with no detected muons); all flux limits here are for the integral flux above 50 TeV assuming an integral power-law spectral index of -1.0.

The phaseograms for the different data sets were constructed in an effort to search for emission correlated with the 4.8 hr period of Cygnus X-3[3]. There is no evidence of such a correlation.

There is no evidence for either pulsed or unpulsed emission during the week following either of the radio bursts. The 90% CL upper limit for the flux for the week after the first burst is $2.5 \times 10^{-12} cm^{-2} s^{-1}$ ($1.0 \times 10^{-12} cm^{-2} s^{-1}$ for events with no detected muons) and for the week after the second burst it is $8.4 \times 10^{-13} cm^{-2} s^{-1}$ ($6.2 \times 10^{-13} cm^{-2} s^{-1}$).

The day with the largest excess, UT 23 July 1989 (JD 2447730.5), is about two days after the second burst, with 104 from the source bin when only 77.3 were expected. The probability for this excess to have occurred from a statistical fluctuation in the entire data set is about 18%. However, if the fact that this day is only two days after the second burst is considered important to establish a correlation with the burst, the probability is about 1%. Most of our excess is concentrated during two hours (about UT 7:30 to UT 9:30). If the excess during this day is considered as evidence for a burst, it would correspond to a flux of about $5.3 \times 10^{-12} cm^{-2} s^{-1}$ averaged over the entire day and about $1 \times 10^{-11} cm^{-2} s^{-1}$ during the two hours. The 4.8 hr phase of Cygnus X-3 during these two hours was between 0.8 to 0.2.

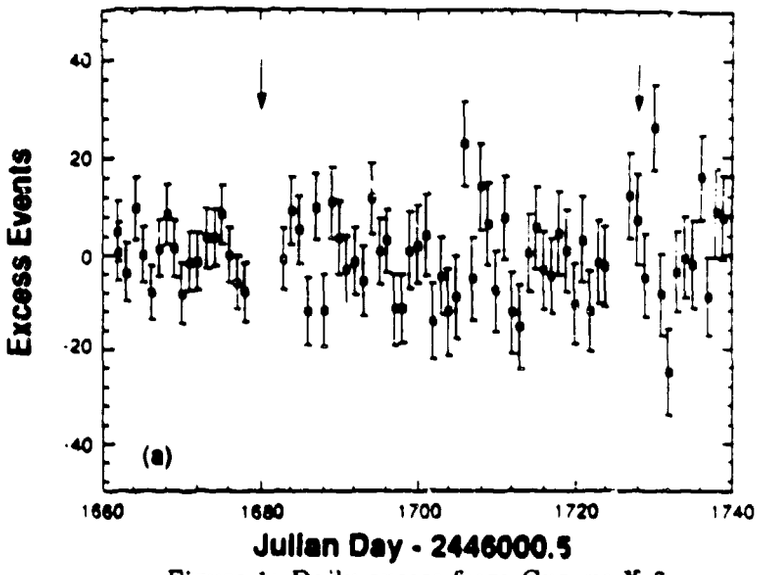

Figure 1: Daily excess from Cygnus X-3.

At low energies ($\sim$ 100 MeV), the plane of the galaxy is, except for a few powerful point sources, the dominant source in the sky. The photons at these energies are primarily produced by cosmic rays interacting with the interstellar medium to produce π^0's. This same mechanism must occur at ultra-high energies as well; therefore, the galactic plane is expected to be a continuous source of γ-ray's. The predictions for the fraction of the cosmic ray flux due to these γ-ray's range from 10^{-5} to 10^{-3}. These predictions depend on quantities that are not well measured like the galactic cosmic ray confinement time, the interstellar density, and the galactic cosmic ray flux. Additionally, the cosmic ray flux seems to be anisotropic, with a sidereal modulation observed, at least, at higher energies. Finally, the "right ascension" an technique for point source searches, as described above, is not well suited to search for many different point sources, especially if they have yet to be identified. It is for these reasons that a technique has been developed to calculate the expected cosmic ray background at every point in the northern sky.

The goal of this analysis is to produce a "background" sky map, that is, the number of events expected from each point in the sky assuming there is no source present there; the analysis has been done on a sample of about 23 million air shower events taken during the first 2 years of operation. This map can then be compared to the observed number of events from every point in the sky in an effort to search for structure. The background map is calculated by first accumulating the distribution of the observed events in local coordinates (zenith and azimuth). For each actual event time, 10 "background events" are chosen randomly from the local coordinate distributions. The celestial coordinates of these events are then used to produce the "background" sky map; these events represent a sample that is as equally likely to have been observed from the cosmic ray background as the actual events, assuming no sources are present and the cosmic rays are isotropic. The advantage of this technique is that the exact running conditions of the experiment are included in the background calculation: the relative exposure to each part of the sky, the trigger conditions

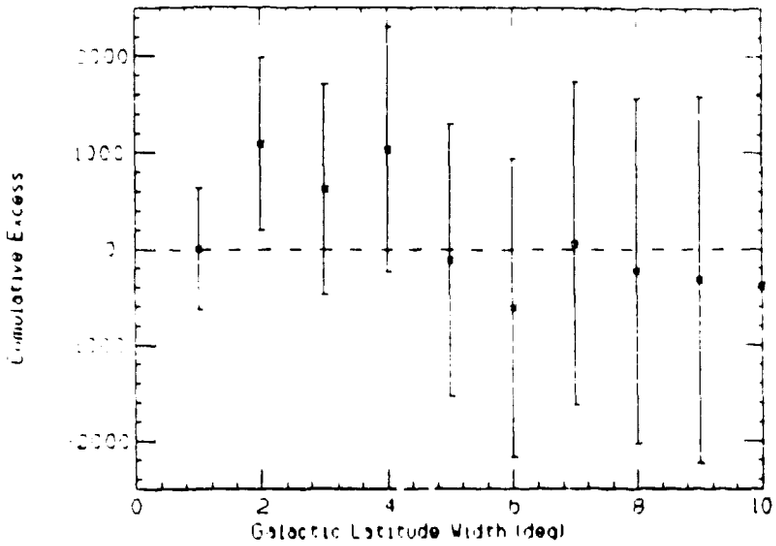

Figure 2: Cumulative excess from the galactic plane as a function of galactic latitude.

on each day, and the trigger rate at each time of day (dependent, for example, upon the local air pressure) are all accounted for. Monte Carlo studies have shown that simulated signals from point sources as well as diffuse sources, such as the galactic plane, are found while effects due to, for example, exposure biases are removed.

The search for diffuse emission from the galactic plane is then straightforward: the observed data is compared with the expected background in galactic coordinates. Figure 2 shows the preliminary result of the excess from the galactic plane. Because the width of the diffuse region at ultra-high energies is unknown, the excess is accumulated as a function of galactic latitude for all galactic longitudes (longitudes from about 30° to about 210° are observable from our site, we do not see the galactic center). Since there is not a significant excess at any latitude, a limit on the fractional excess and the corresponding flux limit (assuming the spectrum is the same as for the cosmic rays) is shown in Figure 3, again as a function of galactic latitude. For an assumed width of ±10° galactic latitude, the 90% CL upper limit on the fractional excess is about 1 part in 1,500 corresponding to a flux limit of 1.1×10^{-11} $cm^{-2}s^{-1}sr^{-1}$.

Evidence for continuous emission from a list of point sources is easily sought using a bin of 2.4° in declination and $2.4°/\cos(\delta)$ in right ascension with this method. A list of potential sources including pulsars, binary x-ray sources, and others, is examined and the excess from each is determined. None of the sources given in Table 1 has a significant excess; therefore, preliminary flux limits, assuming both hard ($\gamma = -1$) and cosmic ray spectral indices, are also given in the Table.

Only slightly more difficult is searching for evidence of emission from "unknown," or at least unspecified, sources. The entire sky from 0° declination to 80° declination is divided into bins of 2.8° in declination by $2.8°/\cos(\delta)$ in right ascension and the excess in each bin is calculated. There are about 2,550 such bins in the sky with some regions ( ) excluded because of technical problems with the data there. This procedure is repeated by moving

Source	Limit Frac. Excess	Flux Limit CR Index	Flux Limit Hard Index
CygX3	0.0130	5.59	1.86
HerX1	0.0133	5.68	1.89
Crab	0.0195	8.34	2.78
VirgoA	0.0213	9.13	3.04
K5	0.0195	8.38	2.79
Geminga	0.0240	10.28	3.43
K4	0.0168	7.20	2.40
K1	0.0162	6.95	2.32
4U0115+63	0.0288	12.36	4.12
K6	0.0143	6.15	2.05
M31	0.0202	8.67	2.89
1E2259+58	0.0154	6.58	2.19
2CG095+04	0.0189	8.11	2.70
2CG078+00	0.0130	5.56	1.85
2CG065+00	0.0137	5.85	1.95
PSR1953+29	0.0138	5.91	1.97
PSR1937+21	0.0153	6.57	2.19
PSR1929+10	0.0197	8.43	2.81
401907+09	0.0197	8.43	2.81
PSR0950+08	0.0217	9.31	3.10
2CG135+01	0.0168	7.19	2.40
2CG121+04	0.0190	8.13	2.71
4U0042+32	0.0134	5.76	1.92
4U0316+41	0.0136	5.83	1.94
4U0352+30	0.0142	6.07	2.02
4U0614+09	0.0274	11.76	3.92
4U1837+04	0.0237	10.15	3.38
4U1901+03	0.0329	14.08	4.69
4U1918+15	0.0172	7.36	2.45
4U2321+58	0.0154	6.59	2.20
4U1257+28	0.0142	6.07	2.02
4U1813+50	0.0137	5.86	1.95
4U1957+40	0.0372	15.94	5.31
PSR1957+20	0.0154	6.62	2.21
PSR0355+54	0.0146	6.28	2.09

Table 1: Point source 90% CL limits. Frac. excess is the limit on the fractional excess from the source; flux limits are in units of $10^{-13}cm^{-2}s^{-1}$.

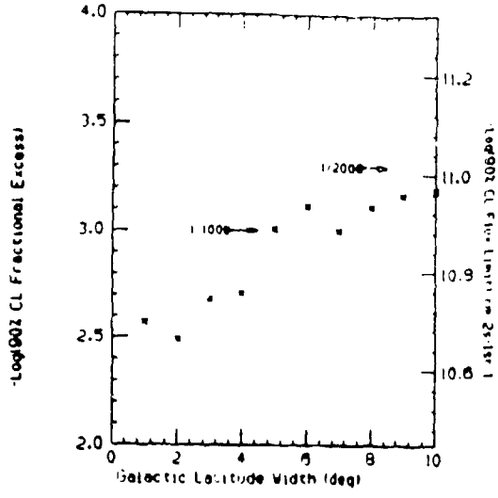

Figure 3: 90% CL limit on the cumulative fractional excess from the galactic plane and the corresponding flux limit.

each bin by 1/2 of a bin width in declination, by 1/2 of a bin width in right ascension, and by 1/2 a bin width in both declination and right ascension, to allow for the possibility that a source is not well centered in a bin. No bin of these four (non-independent) samples has a significant excess after accounting for the total number of bins in the sky. Since a flux limit from each point in the sky is difficult to present, Figure 4 gives corresponding flux limit for each bin, as a function of declination, assuming no excess in the bin of interest.

Although the field of ultra-high energy astronomy is gaining intense worldwide interest and the experiments are continually improving, positive source detections are still rare. There is yet to be an established "standard candle" at these energies, either because no such source exists or because it is too faint to have been detected. Nonetheless, the implications that these studies have had, and will continue to have, for the fields of both astrophysics and particle physics are great enough to warrant the increasing interest in this field for the future.

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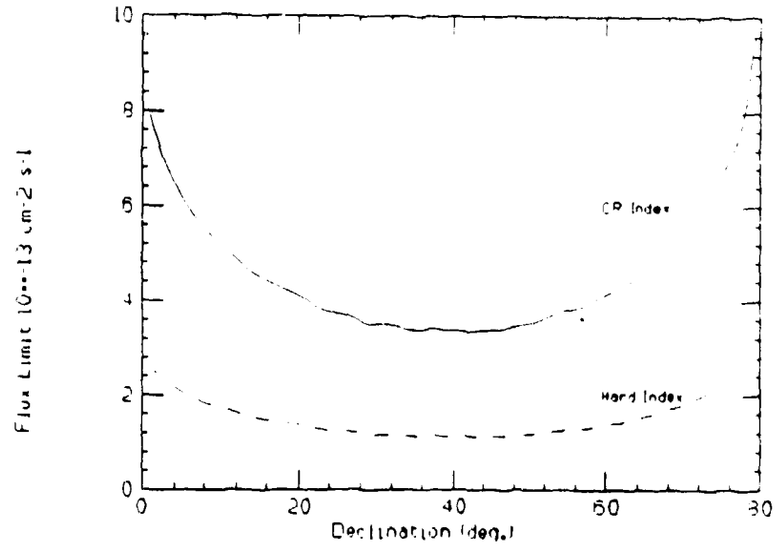

Figure 4: The point source flux limit for each point in the sky assuming no excess at that point.

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[2] for a review see R.J. Protheroe, Proc. of the 20th Int. Cosmic Ray Conf., V.A. Kozyarivsky *et al.*, eds., (Nauka, Moscow) **8**, 21(1987) and references therein.

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