ARTICLES

Search for discrete sources of 100 TeV gamma radiation

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The Chicago Air Shower Array is a large-area ground-based detector designed to observe extensive air showers produced by primary particles with energy $\gtrsim 100$ TeV. It operates in coincidence with the underground Michigan Muon Array. Data taken during 1989 are examined for evidence of continuous and pulsed emission from localized regions of the sky. The x-ray sources Cygnus X-3, Hercules X-1, and the Crab Nebula and pulsar are examined for steady and periodic γ-ray emission. To search for previously unknown compact sources, the background of cosmic rays is estimated over the sky between declinations $+5°$ and $+90°$ and enhancement is sought in small angular bins. There is no evidence for a significant excess from any of these searches, and flux limits are presented as a function of declination and muon content.

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I. ARRAY PARAMETERS

The Chicago Air Shower Array (CASA) and the Michigan Muon Array (MIA) are located at Dugway, Utah (40.2° N, 112.8° W) at an atomospheric depth of 870 g cm^{-2}. Detailed descriptions of CASA [1–4] and MIA [5] can be found elsewhere. From 1 February 1989 through 30 November 1989, CASA operated with 49 detector stations, approximately 5% of the present array size [2]. Each station contains four scintillation counters, totaling 1.5 m^2. These stations are arranged on a 15-m square grid of total enclosed area 8100 m^2. The muon array measures the penetrating component of air showers. During 1989, MIA consisted of 512 buried counters, each of area 2.5 m^2, clustered into eight patches. The average event rate recorded by CASA was 1.2 Hz over 232.6 days of live time, yielding 24.6×10^6 total events. Most of the dead time was due to array development and maintenance. CASA's low trigger threshold accepts some showers too small to permit proper reconstruction. This analysis is based on 22.0×10^6 events with total shower size, or number of charged particles, $N_e\geq1000$ and reconstructed zenith angle $\theta\leq60°$.

The shower arrival direction is determined from the fast timing differences between adjacent stations; thus the time resolution of the individual detectors and fluctuations of particle arrival times govern the statistical angular resolution of CASA. The resolution is measured using the "split detector" technique [2] in which half of the counters in each station are assigned to one subarray (A) and half to another (B). Each subarray provides a separate, but not totally independent, determination of the incident shower direction. A simulation is used to estimate the degree of correlation $f(N_e)$ between these measurements [6]. The space angle difference δ_{AB} between the directions can then be related to the angular resolution of the array as a whole. The distribution of reconstructed events from a point source is assumed to be of the form of a two-dimensional Gaussian distribution of variance σ^2. The CASA resolution $\sigma_{63}(=\sqrt{2}\sigma)$ is defined as the half-angle of the cone which would contain 63% of the events from the point source [7]. The statistical angular resolution is found to improve as N_e increases:

$$\sigma_{63}(\text{deg})=\sqrt{2}f(N_e)\delta_{AB}\approx69.0(N_e)^{-0.39}\ , \tag{1}$$

and at the average shower size of $N_e=2\times10^4$, $\sigma_{63}\approx1.3°$, a value much larger than the systematic pointing errors. The systematic pointing errors of the array are $\lesssim\pm0.1°$, as determined by an independent array of four Čerenkov telescopes [8].

To determine a flux level associated with an observation, it is necessary to characterize the energy response of the experiment [9]. By using the data to determine the effective area and live time of the experiment, the absolute flux of showers is calculated from the observed shower rate. This flux is then parametrized as a function

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of N_e and overburden, which is related to atmospheric pressure and zenith angle. The observed flux is related to primary energy (E) using the cosmic-ray energy spectrum measured by previous experiments [10], assuming a constant particle composition. The relationship is given by

$$E_p = (73.3 \text{ TeV}) \left[\frac{N_e}{10\,000} \right]^{0.92} \exp[0.19(X - X_0)] \ , \qquad (2)$$

where X is the number of radiation lengths through which the shower passed and $X_0 = 24.0$. The median observable hadronic shower energy is calculated to be $140 \pm 7 \pm 20 \pm 28$ TeV. The errors are based, respectively, on uncertainties in calculating the shower flux, uncertainties based on errors in shower size reconstruction, and uncertainties in the parametrization of the cosmic-ray spectrum. The energy spectrum observed by CASA is consistent with that derived, using a similar method, from the Akeno experimental data [11].

Showers initiated by γ-ray primaries undergo a different developmental process than do hadronically induced showers. Therefore the relationship between size and energy should take a different form for γ rays. Parametrizations by Fenyves *et al.* [12] of the longitudinal development of simulated proton showers are found to match similar curves observed by CASA, when the latter are adjusted to account for the presence of CASA's lead converter [2]. The parametrizations of Fenyves *et al.* are used to derive a zenith-angle-dependent scale factor relating hadronic and γ-ray primary energies to observed shower size. Using this relationship, the energy of the γ-ray primary which would have produced each shower observed by CASA can then be estimated. The median observable γ-ray energy is approximately 150 TeV, which, given the altitude of CASA, is nearly the same as the median hadronic shower energy.

By fitting the lateral electron and muon density profiles of each shower to the appropriate distribution function, estimates are made of N_e and the number of muons in the shower, N_μ. The lateral distributions are found to be well represented by the parametrizations of Greisen [13], when using a fixed shower age of 1.28 [14] and distance scales of 64 and 300 m for electrons and muons, respectively. The average muon size is found to be related to N_e by [9]

$$\langle \log_{10} N_\mu \rangle = -0.62 + 0.54 \sec\theta + 0.78 \log_{10}(N_e) \ . \qquad (3)$$

Since most detected air showers are hadronic in origin, $\langle N_\mu \rangle$ can be taken as the expected number of muons for a hadronic shower of given N_e and θ. Simulations of extensive air showers [15,16] show that, at the energies of interest for CASA, the muon content of a γ-ray-induced shower is diminished by an average factor of more than 30 relative to that expected for a hadron-initiated shower. A cut was chosen to optimize the fraction of hadron showers rejected and γ-ray showers retained. A shower having either a muon size such that $N_\mu < \frac{1}{10} \langle N_\mu \rangle$ or less than two detected muons is considered to be muon poor and hence a γ-ray candidate. More than 97% of large simulated γ-ray showers [16] ($N_e > 10\,000$) are correctly identified as muon poor. Among smaller showers ($N_e < 5000$), accidental muon hits will result in a misclassification of $\sim 15\%$ of γ-ray showers as muon rich. Approximately 15.1×10^6 events contain muon information from the MIA detector; 1.3×10^6 of these events are muon poor. The hadronic shower rejection factor H_μ is approximately 11 if it is assumed that all background showers are hadronic in origin; if the background contains a substantial fraction of showers initiated by γ rays, then a greater percentage of hadrons will be rejected. The finite extent of the array can lead to an underestimation of N_e for showers whose cores fall outside the array. Similar results arise as a result of saturation effects for larger showers. These errors tend to increase the number of muon-rich events, hence leading to a smaller and more conservative value of H_μ.

II. SEARCH FOR SELECTED ASTROPHYSICAL SOURCES

A search is made for continuous (dc) ultrahigh-energy (UHE, $E_\gamma > 10^{14}$ eV) γ-ray emission from two objects which have been previously reported as UHE sources [17–20]: the binary systems Cygnus X-3 and Hercules X-1, and from the Crab Nebula and pulsar, which has been confirmed as a very-high-energy (VHE, $E_\gamma > 10^{10}$ eV) source [21]. After correcting event arrival times to the solar system barycenter, the time modulation of showers from these directions is also studied.

Signal candidate events are those falling into a square space angle bin centered on the source (at declination δ) with size $\Delta\Omega$ measuring $2\langle \sigma_{63} \rangle$ in δ and $2\langle \sigma_{63} \rangle / \cos(\delta)$ in right ascension, where $\langle \sigma_{63} \rangle = 1.3°$. The background is determined as follows [22]. The acceptance of the array as a function of horizon coordinates (θ, ϕ) is calculated from the data for every universal time (UT) day. The weight associated with a particular acceptance bin measuring 1° (θ) by 3° (ϕ) is defined as the number of events collected in that bin during the day, divided by both the solid angle of the bin and the total number of events recorded from all directions during the day. Therefore the weight for a given bin reflects the probability that the reconstructed arrival direction of any randomly selected event falls within that bin. The changing horizon coordinates of the source, due to its apparent motion across the sky, cause the source to cross many acceptance bins throughout each transit. For every recorded event, regardless of its direction, the background sum is incremented by the weight associated with the acceptance bin containing the source at that instant. This technique properly accounts for variations in both exposure and acceptance. Excellent statistical precision is achieved from the large number of events used in the background determination. The background and observed counts for a region near Cygnus X-3 are shown in Fig. 1. Good agreement between these numbers suggests that the background has been accurately determined.

For each of the source candidates, Table I lists the numbers of observed and expected background events from the full data set as well as from the muon-poor sample. No significant excess was observed from any of these

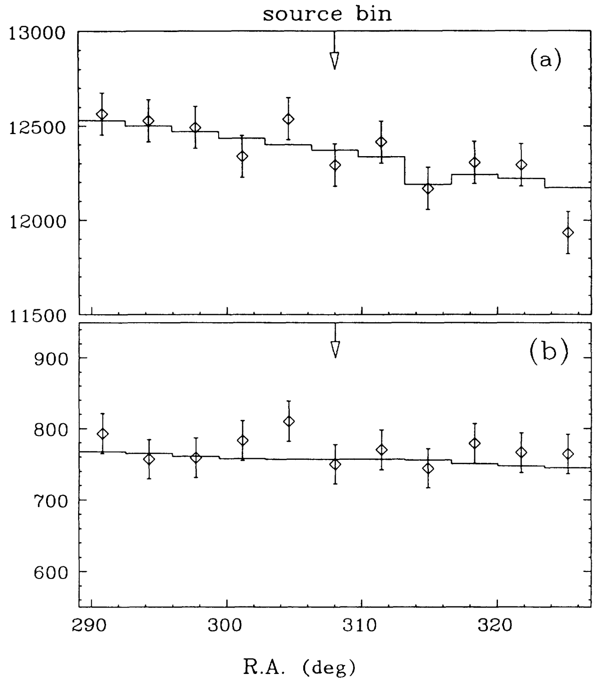

FIG. 1. 1989 total background (histograms) and observed counts (plot points) for 11 contiguous bins at the same declination as Cygnus X-3. The error bars show the magnitude of a one-standard-deviation fluctuation in the signal, and in both figures the source bin is at the center. (a) Uncut data. (b) Muon-poor data. These figures show that the estimate of the background matches the observed number of events, even when the background varies as a function of right ascension.

regions. Using the assumptions that the background is due solely to hadronic showers and that the detection efficiency for γ rays with energies above E_γ is the same as that for hadrons above E_{cr}, flux limits Φ_γ can be derived using the relation

$$\Phi_\gamma(>E_\gamma)<\frac{N_{max}\Phi_{cr}(>E_{cr})\Delta\Omega}{F_\gamma N_{cr} H_\mu} . \quad (4)$$

Here N_{max} is the upper limit on signal counts corresponding to the desired confidence level using the method of Helene [23]. The factor $\Phi_{cr}(>E_{cr})$ is the flux of cosmic rays above the threshold for hadronic showers, N_{cr} is the number of background counts, and $F_\gamma(=0.72)$ is the fraction of events from a point source expected to be contained in the search window. Daily excesses for each source transit were calculated [9], using the prescription of Li and Ma [24], and the resulting distributions of excesses are Gaussian in form with zero mean. Such a distribution for Cygnus X-3 is shown in Fig. 2. The data include no anomalous days for any source. No significant excesses were observed on or shortly following 2 days on which major radio outbursts from Cygnus X-3 were reported [25].

The x-ray emission from Cygnus X-3 is periodic on a time scale of 4.8 h. Previously reported UHE signals [17] have exhibited a similar time structure. The parabolic x-ray ephemeris compiled by van der Klis and Bonnet-Bidaud [26] is used to determine the phase for each event. The data, both signal and background, are divided into 20 phase intervals of equal width. The phase is determined for every event contributing to the background. The appropriate phase bin is then incremented with a weight derived from the acceptance bin containing the source. Figure 3 shows the signal and background for each of these bins. The 2.9σ fluctuation near phase 0.25 may be contrasted with the -2.2σ fluctuation near phase 0.45. Obviously, no significant enhancement appears in any phase bin.

Three groups reported noncontemporaneous pulsed short-term bursts at VHE and UHE from Hercules X-1 during 1986 [18,27]. As in these earlier analyses, event times are corrected to the Hercules X-1 binary system barycenter using the ephemeris of Deeter, Boynton, and Pravdo [28]. The data are searched for periodicity around the ~1.24-sec x-ray period. X-ray observations show that the period and period derivative are variable [29] and no regular updated ephemeris is available for Hercules X-1. Therefore, in order to maintain phase coherence, short data intervals consisting of single source transits are used. The effective observation time during a source transit is approximately 4 h. The source completed 268 such transits during the interval under considera-

TABLE I. Event totals and flux limits from the 1989 CASA-MIA data run for three possible point sources. The upper limits on signal counts are calculated using the method of Helene [23]. Flux upper limits are quoted at the estimated median energy for detectable γ-ray-initiated showers from the source directions, assuming that the γ-ray spectral index is the same as that for cosmic rays. The muon-poor data set consists of showers with less than 10% the muon content expected for hadronic showers.

Source	Events obs./ background	Signal upper limit (90% C.L.)	Flux (90% C.L.) ($cm^{-2}\,sec^{-1}$)
All data			
Cygnus X-3	12 293/12 370	144	$<3.5\times10^{-13}$ (110 TeV)
Hercules X-1	11 868/11 774	252	$<6.6\times10^{-13}$ (110 TeV)
Crab Nebula	6696/6706	132	$<4.2\times10^{-13}$ (160 TeV)
Muon-poor data			
Cygnus X-3	750/757	43	$<1.5\times10^{-13}$ (110 TeV)
Hercules X-1	742/735	51	$<1.9\times10^{-13}$ (110 TeV)
Crab Nebula	396/412	26	$<1.2\times10^{-13}$ (160 TeV)

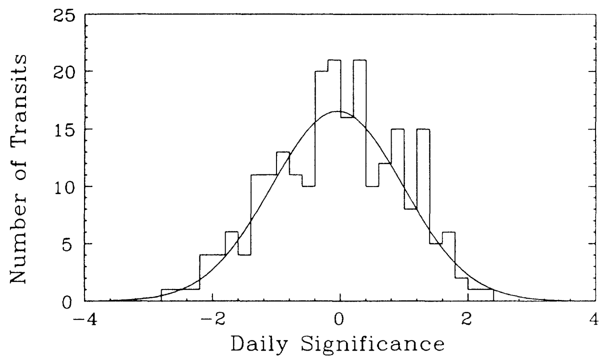

FIG. 2. Distribution of daily significances for 230 transits of Cygnus X-3. No anomalous days were observed. The solid line is a fit to a Gaussian distribution with mean -0.054 ± 0.063 and standard deviation 1.0433 ± 0.069. The mean is consistent with zero as expected for no signal. The large variance is an artifact of the statistics with small numbers of events.

tion; because of limited statistics, periodicity analysis was possible in only 229. A period scan is performed over a range of 120 independently spaced periods centered around the 1.237 792-sec x-ray period. This search is oversampled by a factor of 5. The scan covers the 1.236 85-sec blueshifted period reported at UHE [18] by the Cygnus Collaboration at Los Alamos. In the absence of strong *a priori* information concerning the form of the light curve, the Z_2^2 statistic [30], which is based on the Rayleigh test and is sensitive to both narrow and broad phase peaks, was chosen for this analysis. The seven transits with $\geq 2\sigma$ dc significance are first searched in decreasing order of significance. The largest value of Z_2^2 observed in this subset is 10.39, occurring in transit 37 (days 84.319–84.731 UT). The search is then extended to all transits, and the largest value of Z_2^2 obtained is 16.38, occurring in transit 86 (days 144.137–144.569 UT). The resulting periodogram for transit 86 is shown in Fig. 4. Each chance probability is converted to a significance, and the distribution of significances for all trials is shown in Fig. 5. No significant deviation from the expected Gaussian distribution is observed. After accounting for all trials, the chance probabilities for obtaining Z_2^2 at this level are 11.5% (transit 86) and 73.5% (transit 37). A search for modulation at the 1.7- and 35-day x-ray periods [4] shows no significant correlation with these periods. These data show no evidence for UHE pulsed emission from Hercules X-1.

Recent VHE observations reveal the Crab Nebula as a steady source of γ rays [21]. A 33-msec pulsar is observed in the Crab Nebula at radio, optical, and x-ray wavelengths and in low-energy (<1 GeV) γ rays [31], but there is no evidence yet for pulsed emission from the Crab Nebula at VHE or UHE energies. The data are

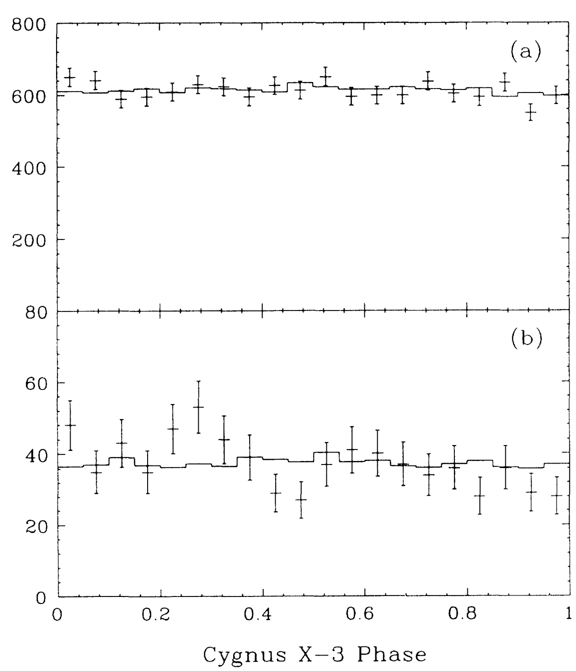

FIG. 3. On-source events (crosses) and expected background (histograms) for Cygnus X-3, plotted as a function of x-ray phase. Zero phase corresponds to x-ray minimum. Plot (a) is based on the full 1989 CASA data set, and (b) uses only muon-poor data.

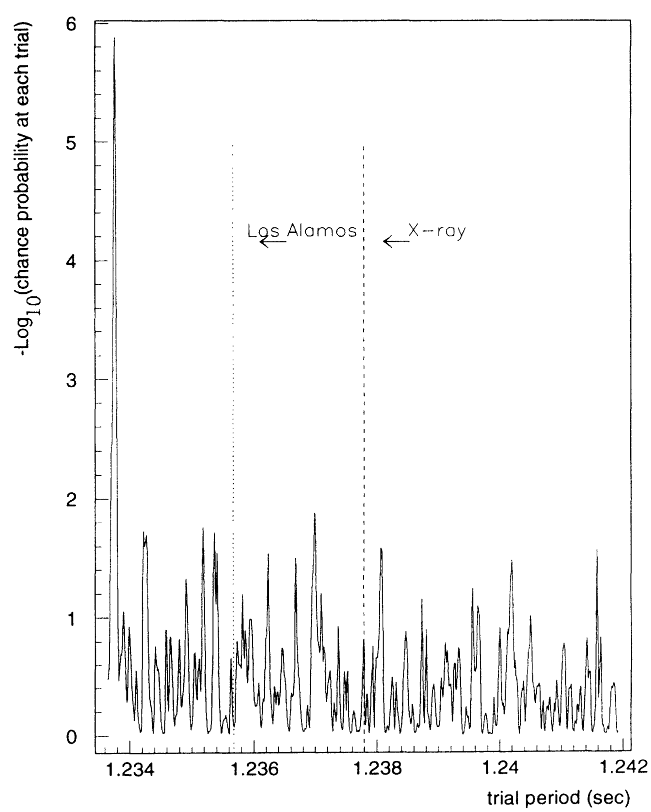

FIG. 4. Periodogram for Hercules X-1 showing the chance probability at each trial as a function of trial period for transit 86. The chance probability to obtain the largest value of Z_2^2 (16.38) seen after searching 229 transits is 11.5%. The x-ray and UHE pulsar periods reported by the Los Alamos experiment are shown.

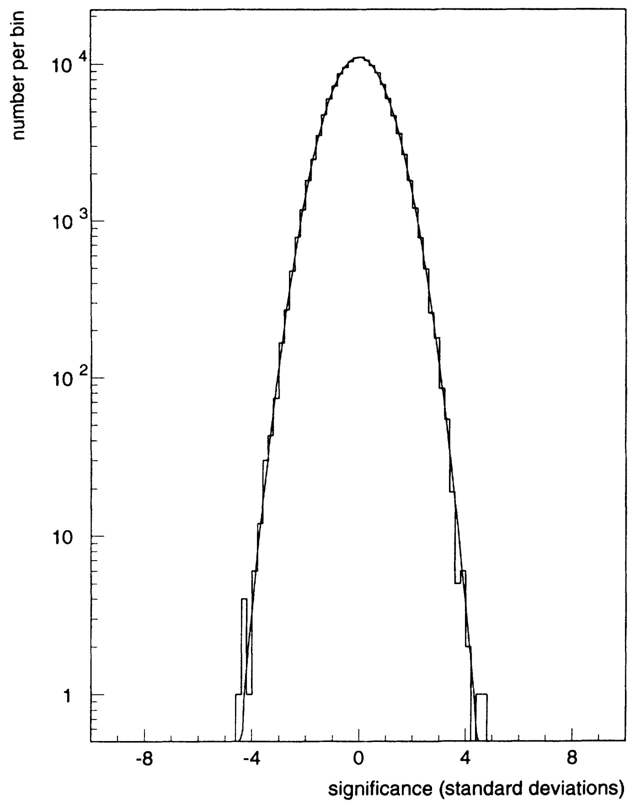

FIG. 5. Distribution of significances computed for each trial period in the search for a 1.24-sec pulsar in Hercules X-1. No significant deviation is observed. the solid line is a fit to a Gaussian distribution with a mean of 0.006±0.003 and a standard deviation of 0.997±0.002.

searched for a 33-msec pulsar in the Crab Nebula using the Jodrell Bank ephemeris [32]. The Z_2^2 test on all the data gives a power of 3.438, corresponding to a 14.2% chance probability. Data are available for 219 of the 270 possible transits. Two transits show a ≥ 2 sigma dc significance, and no transits show a significant pulsed power. Thus there is no evidence in these data for a 33-msec UHE pulsar in the Crab Nebula.

III. ALL-SKY SURVEY

CASA provides good pointing accuracy within a large angular aperture, allowing a search to be made for previously undetected sources of UHE γ-ray emission. CASA is sensitive to showers with zenith angle $0° \leq \theta \leq 60°$, corresponding roughly to declinations $+5° \leq \delta \leq +90°$. This region of the sky is examined for continuous flux from point sources using both the full data set and the muon-poor sample. The search method is designed using the following considerations. The choice of the size and location of search bins should not bias the survey. If the bin size is comparable to the average resolution, an arbitrary choice of bin locations will result in a lack of sensitivity for sources falling near bin boundaries. Several overlapping surveys would then be necessary. In contrast, if the angular bin size is chosen to be smaller than the average resolution and the number of bins incremented for each event is allowed to vary as a function of event shower size, as does the angular resolution, then the effects of sampling are mitigated. The search method is chosen to maximize the efficiency for identifying point sources while minimizing the chance of false identifications due to random fluctuations.

Approximately 1.83π sr of the celestial sphere is divided into 76 321 nonoverlapping bins of slightly varying shape but equal solid angle:

$$\Delta\Omega \approx 0.5° \times 0.5° = 7.55 \times 10^{-5} \text{ sr} , \quad (5)$$

where 0.5° is the approximate angular resolution for the largest showers observed by CASA. The equatorial coordinates of each shower event determine the most likely direction from which the primary arrived and hence the most probable survey bin. However, finite statistical angular resolution suggests that there is some probability that the event came from another nearby point in the sky. This probability falls off with distance from the calculated direction. To account for this uncertainty in the sky survey, a total weight of 1 is added to the most probable bin and distributed among its neighbors, according to a two-dimensional Gaussian function with width $\sigma = \sigma_{63}/\sqrt{2}$, where σ_{63} is the resolution appropriate to the event shower size N_e, as determined by Eq. (1).

The background is estimated by generating 30 background events for every real event using the real-event zenith angle and sidereal time, but a random azimuthal angle derived from the azimuthal acceptance of the array. Each background event is placed into a single search bin without distributing its probability. A single "random-sky" survey is generated in the same manner as the real-sky survey when one of the 30 background events is treated as if it were a real event. The variance of the "random sky" will be the same as that of the real survey in the absence of any sources. These variances are found to be Gaussian in form up to a scale factor which accounts for the fact that fluctuations in adjacent signal and background bins are not statistically independent.

A Monte Carlo method, in which simulated point sources are superimposed on the random sky, is used to estimate the significance of a given excess and to study the efficiency of the search method for detecting point sources. A procedure is developed [3] with the power to locate to within 1.5° 97% of those point sources with a significance greater than three standard deviations above background. The method falsely accepts only one point from the random sky not corresponding to a simulated source.

The search procedure is now briefly described. Any survey bin with a scaled significance greater than three standard deviations above background is examined. Since the average detector resolution is larger than the size of a survey bin, a genuine signal will produce a significant excess in multiple bins. Therefore isolated "high-significance" bins inconsistent with detector resolution are eliminated. Seventy points in the full data survey and 68 points in the muon-poor survey remain after these cuts.

When 1.5° regions around these points are examined,

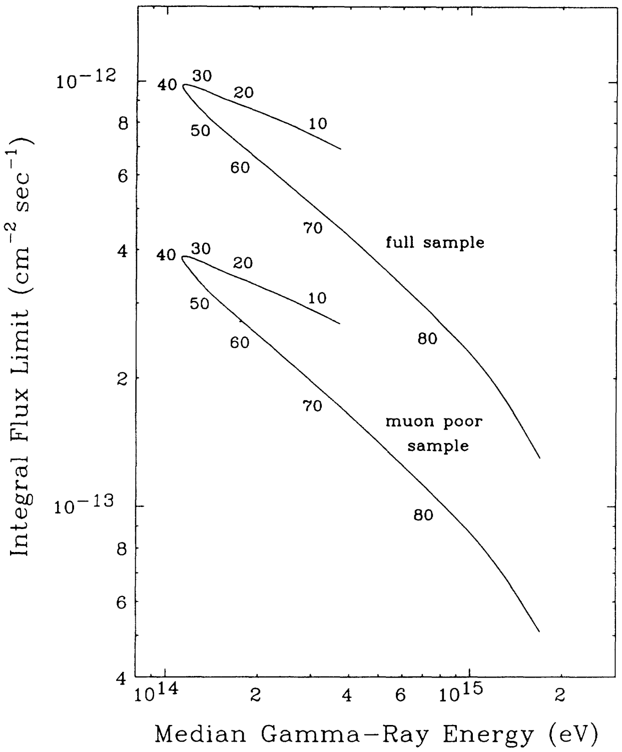

FIG. 6. Integral flux upper limits at a 90% confidence level derived from the 1989 CASA all-sky survey. Numbers on the curves correspond to the declination of a search region. The estimated median energy of observable γ rays from the search direction is plotted vs the corresponding point-source flux limit. For the full data sample the flux limits correspond to a $\sim 4\%$ excess above the cosmic-ray background at $\delta=40°$, rising to $\sim 10\%$ at $\delta=10°$ and 80°. The muon-poor limits correspond to a $\sim 1.5\%$ excess at $\delta=40°$ and $\sim 4\%$ at $\delta=10°$ and 80°. Variation of source exposure with declination at 40° N latitude gives rise to the two separate branches of each curve.

one region ($\alpha=88.7°$, $\delta=20.6°$) is found to have a 2.5σ significance. This corresponds to a chance probability of 43%, from 70 effective trials. The muon-poor sample yields a single point ($\alpha=213.9°$, $\delta=67.5°$) with significance 2.7σ, corresponding to a chance probability of 24%, based on 68 trials. Neither point is within 1.5° of a reported x-ray source, and these numbers are consistent with random fluctuations; thus, no observation can be claimed. Flux limits for point sources are calculated assuming that the excesses observed are consistent with random fluctuations and that the array had uniform exposure in right ascension during the survey period. The limits were calculated using Eq. (4), with values of N_{cr} and E_{cr} averaged over 5° bands in declination. The confidence level was also modified to account for the number of bins searched using the method of Hearn [33]. The limits are presented in Fig. 6 as a function of median energy and declination. It should be noted that the all-sky survey found no significant excesses from the three possible sources discussed in Sec. II.

IV. CONCLUSION

The 1989 data from the Chicago Air Shower Array show no evidence for point sources of ultrahigh-energy γ rays. These results can be compared with previous reports of such emission from Cygnus X-3, Hercules X-1, and the Crab Nebula. The present steady-flux limits for all three potential sources are of comparable sensitivity to other recently reported results at ~ 100 TeV energies [20]. All published reports of UHE γ-ray signals from Cygnus X-3 [17] are derived from experiments operating at energies well above CASA's median energy, making direct comparison difficult. However, if the flux limits reported here are extrapolated to higher energies assuming an integral cosmic-ray spectral index of -1.55, it is seen that these results are inconsistent with previous reports. If, however, the spectral index for γ rays is less steep than that for cosmic rays, CASA may not yet be sensitive to a signal detectable at higher energies. It should also be noted that most of the previously reported observations are derived from an excess at a particular point in the x-ray phase and that this analysis reveals no significant excess in any phase bin. A number of short-term bursts at energies above 100 TeV have been reported for Hercules X-1 [18]. This behavior is not observed in the present analysis. No evidence was seen in this analysis for pulsed emission from the Crab pulsar as had been previously reported [34]. A burst from the Crab Nebula was reported in February 1989 by three different experiments [35]. The CASA detector was not operating at the time of this reported observation, and so it cannot be confirmed or contradicted.

ACKNOWLEDGMENTS

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