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SOURCES BY THE EAS-TOP ARRAY
(1989-1993)

EAS-TOP collaboration

INFN - Laboratori Nazionali del Gran Sasso

RESULTS ON CANDIDATE UHE GAMMA-RAY SOURCES BY THE EAS-TOP ARRAY (1989-1993)

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ABSTRACT. A search for U.H.E. gamma-rays from the candidate point sources observable in the northern hemisphere (the Crab Nebula and Pulsar, Cygnus X-3, Hercules X-1, Geminga and others) has been performed by the EAS-TOP array during a period of operation of four years since January 1989 to December 1993, at different energy thresholds ($E_0 = 30-300$ TeV).

D.C., periodic and sporadic emissions from 13 candidate sources have been studied, and no evidence for significant excesses has been found from any of these searches. The derived 90% c.l. upper limits to the d.c. flux, for a source culminating at the zenith such as Cygnus X-3, are $\Phi(E>230 \text{ TeV}) < 2 \cdot 10^{-14} \text{ cm}^{-2} \text{ s}^{-1}$, $\Phi(E>90 \text{ TeV}) < 4.1 \cdot 10^{-14} \text{ cm}^{-2} \text{ s}^{-1}$ and $\Phi(E>25 \text{ TeV}) < 4.5 \cdot 10^{-13} \text{ cm}^{-2} \text{ s}^{-1}$.

The excess from the Crab Nebula of February 23, 1989, as reported by EAS-TOP in coincidence with the Baksan and KGF arrays, remains the only sporadic excess detected with statistically significant confidence level (probability of background imitation $\approx 10^{-5}$).

1. INTRODUCTION

The search for gamma-ray emission from point sources at TeV and PeV energies is the main tool for understanding, together with the physics of specific stellar objects, the processes of particle acceleration and therefore of the origin of high energy cosmic rays.

Among the motivations supporting the need of new measurements we mention:

- In late seventies and early eighties several groups reported gamma-ray emission from the X-ray binary system Cygnus X-3 at Very High Energy [1] ($E \geq \text{TeV}$) and Ultra High Energy [2-4] ($E \geq 10+100 \text{ TeV}$). These positive results have not been confirmed by subsequent measurements, rising the problem of their statistical significance and/or source variability.

- A significant result has been obtained by the Whipple collaboration [5] with the detection of TeV gamma-rays from the Crab Nebula. The extension of the measurement to UHE is expected to provide information on the maximum energies achieved in the pulsar acceleration mechanisms. Moreover, the possibility of sporadic emission from the Crab Nebula at U.H.E. has been supported by the contemporaneous observation of the burst on 23 February 1989 by three different detectors (Baksan [6], KGF [7] and EAS-TOP [8]), with high confidence level.

- In the High Energy region ($20 \text{ MeV} < E < 20 \text{ GeV}$), the EGRET telescope aboard GRO has extended the class of gamma-ray sources, e.g. by the discovery of the emission from Active Galactic Nuclei [9], and has improved previous knowledge, as for example by the identification of Geminga with a gamma-ray pulsar [10]. Following this observation, two groups [11-12] have reported pulsed TeV emission from Geminga in 1983 and 1984-85 databases, while the Whipple collaboration [13] has set upper limits both to steady and pulsed fluxes. Relating to AGNs, it is recent the observation of TeV gamma-rays emission from Markarian 421 [14].

It is therefore important to perform long lasting systematic measurements at UHE in order a) to extend the knowledge of the VHE spectra, b) to study possible long term source variations, c) to investigate phenomena of episodic emission.

This energy range ($E > 0.1 \text{ PeV}$) can be explored only by means of ground based detectors, i.e. Extensive Air Shower arrays. For such measurements, the main experimental problems are due to the cosmic ray background (given the difficulties of discriminating gamma-rays

from charged primaries), the limited angular resolution, and the usually poor statistics.

The EAS-TOP detector [15-16] has been developed in order to improve: a) the collecting area ($> 10^5 \text{ m}^2$); b) the angular resolution ($\sigma_\theta < 1^\circ$); c) the energy range of operation, by performing contemporaneous TeV and PeV observations at the same site (with further possibility of energy discrimination above 30 TeV); d) the rejection power against hadronic background (through the contemporaneous detection of the e.m., muonic and hadronic components of EAS at PeV energies). The e.m. detector has been in acquisition since the beginning of 1989, for a total, at now, of four full years of operation and $\approx 3 \cdot 10^9$ collected air showers.

We present here the results of an analysis comprehensive of all the events collected in the time period between 1989 and 1993 by the e.m. detector, without any further selection criterium. Results from partial periods of measurement have already been reported, concerning candidate point sources [17-19], periodic transients [8] and an all-sky survey [20]; furthermore a study on the diffuse galactic component has been published in ref. [21].

Recently, results on candidate sources have been reported by other collaborations (see e.g. refs. [22-25]).

2. THE DETECTOR

The EAS-TOP Extensive Air Shower array is located at Campo Imperatore (2005 m a.s.l., lat. $42^{\circ} 27'N$, long. $13^{\circ} 34'E$, Gran Sasso Laboratories). The electromagnetic detector has been in operation since January 1989 under different configurations, being progressively enlarged: in fig. 1 a scheme of the full array is shown, while in table 1 the different phases are summarized.

At present the detector consists of 35 modules of scintillation counters (10 m^2 each, spread over an area $\geq 10^5 \text{ m}^2$). The trigger is provided by any coincidence of four adjacent modules (threshold ≈ 0.3 minimum ionizing particles/module), the rate being $\approx 35 \text{ Hz}$. The absolute arrival time of each event is measured with a precision of $100 \mu\text{sec}$ through a Rubidium clock synchronized with the standard time provided by the Italian national broadcasting company.

While the experiment and the data processing have been described in detail elsewhere¹⁶, the relevant features for gamma-ray astronomy will be outlined here.

Different selection criteria are applied to the data in order to investigate different primary energies and to optimize the angular resolution; the so obtained classes of events are the following:

- S_1 : at least 7 (or 6) neighbouring detectors fired, with the maximum number of particles detected by an inner module (i.e. internal events, rate $f \approx 2 \text{ Hz}$ in the present configuration). The arrival directions are obtained through the times of flight among the detectors located around the EAS core. The angular resolution σ_{θ} is measured by comparing, for each shower, the arrival directions obtained from two independent sets of modules: σ_{θ} is shown in fig. 2, as a function of the EAS average electron size N_e . The measurement [26] of the shape of the Moon shadow on the flux of primary cosmic rays in each successive year of data confirms the angular resolution and provides a check of the absolute pointing of the array and of its stability. In fig. 3 the behavior of the percentage deficit of events vs. the opening angle from the center of the Moon is shown, both for each year and for the global database. The total observed deficit has a significance of 4.1 s.d. and, inside 1.25° , it amounts to 332.5 events out of 4426.5 background ones (measured from two cells located at the same declination as the Moon but shifted in right ascension of $\pm 2\Delta\alpha$, with $\Delta\alpha=1.6^{\circ}$). This deficit (7.5%) corresponds to the absorption of a flux of $1.4 \cdot 10^{-13} \text{ cm}^{-2} \text{ s}^{-1}$, in 1057 hours of observation at an average zenith angle $\vartheta \approx 31.5^{\circ}$. The obtained

overall resolution, converted to the vertical, is $\sigma_{\theta} = 0.85^{\circ} \pm 0.1^{\circ}$, including systematic effects, confirming the data in fig.2.

For internal events, the shower size N_e is also reconstructed, by means of a fit of the particle densities recorded by the individual detectors; the accuracy in the reconstruction of the shower size is $\Delta N_e/N_e < 0.2$.

- S_2 : a subset of S_1 , with the additional selection $N_e > 10^5$, for which $\sigma_{\theta} = 0.5^{\circ}$ (see fig. 2) and $f \approx 0.3$ Hz;

- S_3 : at least five detectors fired, and core location outside or at the edges of the array: σ_{θ} is $\approx 2.5^{\circ}$ and $f \approx 15$ Hz;

- S_4 : only four detectors fired (i.e. the minimum trigger configuration): $\sigma_{\theta} \approx 5.6^{\circ}$ and $f \approx 5$ Hz.

The characteristics of the different classes of events are listed in table 2.

3. THE ANALYSIS

The analysis is performed by searching for statistically significant excesses in the number of counts inside a bin of dimensions optimized on the angular resolution, centered on the source (ON), with respect to six analogous background bins (OFF). The dimensions of the bins are $\Delta\delta=1.58\sigma_\vartheta$ and $\Delta\alpha=\Delta\delta/\cos\delta$ (see tab. 2 for the values of the bin size in δ), being 1.58 the factor which maximizes the ratio of the signal to the background fluctuations in case of a Gaussian angular resolution with r.m.s. σ_ϑ . The method for calculating the statistical significance of any excess is that suggested by Li and Ma [27].

3.1. The C.R. background measurement and its stability.

The C.R. flux has to be measured and monitored since it is the source of the background of the measurement. On the other side, it provides a test of the response of the detector to the UHE atmospheric showers and of its stability: this partially allows to overcome the problem of the absolute calibration, which is not possible for EAS arrays.

EAS-TOP has measured the EAS size spectrum (at 800 g/cm^2): $S(>N_e)=A \cdot (N_e/10^{5.2})^{-\gamma}$, where $A=(3.75\pm0.05) \cdot 10^{-6} \text{ m}^{-2} \text{ s}^{-1} \text{ sr}^{-1}$ and $\gamma=1.69\pm0.01$, for $5.2 < \log(N_e) < 5.7$, i.e. below the steepening of the primary spectrum, which is found at $N_e=10^6$. By using an interaction and cascade model [28] in the atmosphere and in the detectors for the E_0 - N_e conversion, the obtained spectrum [29] is in agreement with that expected from the extrapolations of the direct balloon and satellites measurements. This proves that the behavior of the detector is well understood and that the calculations of the responses in primary energy and of the effective areas (see appendix A) are reliable.

For each source, the background is obtained from the average number of counts ($\langle\text{OFF}\rangle$) from six bins having the same dimensions and located at the same declination of the ON cell but shifted in α of $\pm 2K\Delta\alpha$ ($K=1,3$). Only days in which all the seven cells are observed without interruptions up to the zenith angle $\vartheta=40^\circ$ are used for the analysis. For the full data set about 10% of the observation time has been discarded for this reason. The OFF bins are therefore observed for the same exposure time and at the same zenith angles as the ON one.

The determination of the background through observations close in time to the source ones (within $\pm 1 \text{ hr}$) compensates for smooth variations of the experimental or atmospheric conditions during the transit of the source. A conservative upper limit to possible residual effects can be obtained from the comparison between the number of

counts in the two farthest OFF bins, for each source and for each class of events. All the observed differences are at the level of 2 s.d poissonian fluctuations: the upper limit to not compensated systematic fluctuations obtained from the class of events with higher statistics ($> 10^6$ events) is $8 \cdot 10^{-4}$. The negligible level of non-poissonian fluctuations can also be inferred from the absence of deviations in the distributions of the sources daily excesses with respect to the statistical ones (see e.g. figs. 5, 7, 9, 10).

3.2. Search analysis.

The searches accomplished on candidate gamma-ray sources are for:

- d.c. emission (on the whole dataset and on one-year time scale);
- sporadic emission, on a daily transit time-scale;
- time modulated emission, from sources for which a periodicity is measured at lower frequencies (i.e. $P \approx 4.8$ hrs for Cygnus X-3, $P \approx 33$ ms for the Crab Pulsar and $P \approx 237$ ms for the Geminga pulsar). The arrival times of each event are corrected to the barycentre of the Solar System using the JPL DE200 ephemeris [30]. This procedure is applied both on source and background events.

4. THE RESULTS

Thirteen candidate sources have been studied: they are listed in table 3 together with their observation parameters. The same table shows also the different energy thresholds which depend both on the considered class of events and on the source declination (see appendixes A and B for a complete description of the formalism used to derive energy thresholds, effective areas and fluxes).

We will discuss in detail the results on Cygnus X-3, the Crab Nebula and Pulsar, and Geminga, and we will summarize the results from the other ones.

4.1. Cygnus X-3

- D.C. emission. Due to the possible source variability, the data have been examined both yearly and globally. For each year and for the total observation time, table 4 lists the number of observed events, the background ones and the significances of the excesses at the different threshold energies.

There is no evidence of steady emission both in the whole data set and in the yearly ones. The corresponding d.c. flux upper limits (assuming a source spectrum $\propto E^{-2}$) have been derived (at 90% c.l.) and are shown in tab. 4, being e.g.:

$$\Phi (> 230 \text{ TeV}) < 2 \cdot 10^{-14} \text{ cm}^{-2} \text{ s}^{-1}$$

i.e. $< 1\%$ of the C.R. flux within a solid angle $\Omega = 8 \cdot 10^{-4} \text{ sr}$.

- 4.8 hrs periodic emission. The X-ray cubic ephemeris by Van Der Klis and Bonnet Bidaud [31] have been used to determine the phase of each event; the data, both ON and OFF, have been assigned to fourty phase bins. The light curves have been obtained both for the total period of observation and for each year. No unexpected excess is observed at any phase and at any energy threshold, in any year (the phase plot obtained from the global S_1 data set is shown in fig. 4). The obtained upper limits to the emission in the bin corresponding to phase 0.625 (corresponding to the phase at which the above mentioned emission was observed) have been calculated and are shown in tab. 4 (last column).

- Sporadic emission. Daily excesses significances have been derived and the resulting distributions are for all trigger conditions in optimum agreement with Gaussian ones with mean=0 and s.d.=1 (e.g. for S_1 events: $\chi^2 = 35.5$ for $\nu=49$ degrees of freedom, see fig. 5). In no case the maximum excess S_{max} measured in 786 days has a probability smaller than 10% to be simulated by background fluctuations. At 90% c.l., less

than 1.5 events/year have been observed with flux $> \Phi_s$ and duration ≤ 7 hrs: Φ_s , calculated from $S_{\max}$, is displayed in tab. 5.

The obtained upper limits to the d.c and periodic fluxes are respectively a factor of almost 80 and 300 lower than the fluxes reported in refs. 2-4, showing that, during the period 1989-1993, Cygnus X-3 has not been active at the level of early 80s. Moreover, due to the results of the yearly analysis, a long term variation of the emission can be excluded, at least since 1989 to 1993. Lastly, no evidence of significant source activity has been found in any observation day, including those corresponding to radio bursts [32] (June 1989, July 1989, August 1990, October 1990).

4.2. Crab Nebula and Pulsar

- D.C. emission. As it can be seen from table 6, no evidence for steady emission has been found at any energy threshold. Using a differential energy spectrum $\propto E^{-2.4}$ [5], upper limits to the flux have been obtained: they are reported in tab. 6, the one closest to the TeV observations being:

$$\Phi (> 25 \text{ TeV}) < 4.7 \cdot 10^{-13} \text{ cm}^{-2} \text{ s}^{-1}$$

corresponding to $< 0.05\%$ of the the C.R. flux within 0.019 sr.

- Pulsed emission. The ≈ 33 ms pulsar periodicity has been searched by using the Jodrell Bank ephemeris [33]. Each event arrival times have been folded into 33 channels phasograms: figures 6a and 6b show such light curves obtained with S_1 and S_2 events respectively (the phases of optical pulses, main and interpulse, are indicated). Since no channel shows unexpected excesses, the upper limits to the emission in the bin corresponding to the main pulse ($\Delta t = 1$ ms) have been derived and are reported in last column of tab.6.

- Sporadic emission. No unexpected excess is observed in any daily excesses distribution: such distribution for S_1 events is shown in fig. 7, being its $\chi^2 = 40$ for $\nu=49$ with respect to a reduced Gaussian (also shown in the figure). The derived flux limits Φ_s are presented in tab. 7: at 90% c.l., less than 1.5 events/yr have been observed with a flux $> \Phi_s$ and duration ≤ 5.5 hrs (for a similar search concerning the epoch since 1982 to 1986 see ref. [34]).

The study of transient phenomena through contemporaneous observations by different arrays is thus most important. Of particular significance is the burst recorded on 23rd February 1989 from the direction of the Crab Nebula by the Baksan [6], KGF [7] and EAS-TOP [8] arrays. The three experiments detected an excess of showers, at the

transit times of the Crab Nebula over them: a summary of the three observations is given in table 8.

The significance of the event recorded by the EAS-TOP array alone is 2.4 s.d. (the excess found in S_1 events is indicated by an arrow in fig. 7) and the observed flux in ≈ 5.5 hours of observation is:

$$\Phi (>200 \text{ TeV}) = 2 \pm 1 \cdot 10^{-12} \text{ cm}^{-2} \text{ s}^{-1}.$$

This event, which has a total probability of being simulated by background fluctuations $\approx 10^{-5}$, still stands as the most significant excess recorded at UHE energies.

4.3. Geminga

- D.C. emission. The results of a search for a d.c. excess are summarized in table 9.

No statistically significant excess has been detected; the derived upper limits to the flux (source spectrum $\propto E^{-2}$) are shown in the same table, being e.g.:

$$\Phi (> 40 \text{ TeV}) < 6.6 \cdot 10^{-13} \text{ cm}^{-2} \text{ s}^{-1}$$

corresponding to 0.05% of the C.R. flux within 0.019 sr.

- Pulsed emission. Following the observation of a pulsed signal, with a period of ≈ 0.237 s, both in X-rays [35] and in 300 MeV gamma-rays [10], a pulsed UHE gamma-ray emission has been searched in the EAS-TOP most recent data (namely 1992 and 1993), using the position of the X source G" (R.A. = 6h 33m 54.02s, DEC. = $+17^\circ 46' 11''$ in 2000 [36]) and the EGRET ephemeris [37-38]. The uncertainties on such ephemeris make possible to fold the arrival times into a 20 bins light curve for our whole observation time, the binning being decided a priori so that the phase of EGRET "peak 1" coincides with the center of a bin.

First results based on ≈ 1200 hrs. of observation since December 1991 to January 1993 have been presented in ref. [39]. The S_3 events (which showed a slight excess at 1.5 s.d.) were subjected to a periodic analysis using the pulsar ephemeris given in [37]: the resulting light curve showed 2.5 and 3.1 s.d. excesses in the two bins corresponding to the phases of EGRET peak 1 and peak 2. Including the fact that four data sets were searched, the overall imitation rate of the excess resulted to be $2 \cdot 10^{-4}$.

The hours of observation has now increased to ≈ 2200 , extending until December 1993: table 10 shows the collected number of counts together with their significances, for all the trigger conditions.

The S_3 data set still presents a slight d.c. excess at 1.7 s.d.: the arrival time of each event has been folded using the most recent pulsar ephemeris [38]. The obtained light curve is shown in fig. 8: the two

arrows indicate the phases of peak 1 (P1) and peak 2 (P2). The light curve shows only one excess in the bin corresponding to peak 1: it contains 52971 events while 52190 are expected from a uniform distribution of the background into the 20 bins, corresponding to an excess of 3.4 s.d.

Taking into account the total number of data sets analyzed (4) and the number of peaks of the emission (2), the overall imitation rate is $2 \cdot 10^{-3}$. This is not low enough to allow a definite conclusion; therefore we derive the 90% c.l. upper limit to the pulsed emission in the two pulsar peaks:

$$\Phi (>45 \text{ TeV}) < 1.4 \cdot 10^{-13} \text{ cm}^{-2} \text{ s}^{-1}$$

- Sporadic emission. All the excess distributions are well described by a reduced Gaussian behavior (χ^2 is 39 with $\nu=49$ for S_1 events, see fig.9) and no unexpected excess has been found. The derived flux limits Φ_s are shown in table 11: < 1.5 events/yr (at 90% c.l.) with a flux $> \Phi_s$ and duration ≤ 5 hrs.

4.4 Other candidate sources

Ten other candidate point sources have been examined (table 12 shows the number of days of observation ON source and the total number of collected events).

- Long term emission. No statistically significant d.c. excess has been found from any of the observed sources, at any energy threshold: tab. 12 shows the results and the 90% c.l. upper limits (assumed source spectra $\propto E^{-2}$).

- Sporadic emission. We discuss more in detail the observations of Hercules X-1, in the past reported as a sporadic UHE emitter (see e.g. ref. [40]): the distribution of the daily excesses in the direction of Hercules X-1 is shown in fig. 10 for S_1 events (where the comparison with a reduced gaussian distribution gives $\chi^2 = 25$ for $\nu=49$). No unexpected excess has been recorded at any energy threshold: the 90% c.l. upper limit gives a rate < 1.1 events/year with flux $> \Phi_s$ and duration ≤ 7 hrs. The values of Φ_s are given in table 13, together with the data on the other investigated sources which also showed no evidence of sporadic emission.

5. CONCLUSIONS

We have presented the results obtained from four years (1989-1993) of systematic observations of the EAS-TOP e.m. detector in the search for UHE gamma-ray emission from candidate point sources observable in the northern hemisphere.

The detector angular resolution is $\sigma_\theta \approx 0.85^\circ$ at energy $E_0 \approx 100$ TeV ($\approx 0.5^\circ$ at ≈ 250 TeV): this is checked for each successive year of operation through the shadowing effect on the cosmic rays flux by the Moon. Moreover, the counting rate stability has been systematically monitored, the upper limit to the level of instabilities being $< 0.08\%$.

Thirteen sources have been studied concerning possible d.c., sporadic and periodic emission: no evidence for significant excess has been found and upper limits have been placed.

In the case of Cygnus X-3, the limits (e.g. $\Phi_{\text{d.c.}} (> 230 \text{ TeV}) < 2.0 \cdot 10^{-14} \text{ cm}^{-2} \text{ s}^{-1}$, $\Phi_{4.8\text{hrs}} (> 230 \text{ TeV}) < 3.2 \cdot 10^{-15} \text{ cm}^{-2} \text{ s}^{-1}$) are well below the fluxes reported in early '80s (a factor ≈ 80 and ≈ 300 respectively for d.c. and periodic signals). Moreover, a long term variation in the emission can be excluded, due to the yearly analysis, at least since 1989 to 1993.

The upper limits obtained from the Crab Nebula are at the level of the extrapolation of the measured $0.5\div 5$ TeV flux to the energy region around 30 TeV ($\Phi (> 25 \text{ TeV}) < 4.7 \cdot 10^{-13} \text{ cm}^{-2} \text{ s}^{-1}$). The results obtained in the search for sporadic emission is negative at a flux level $\approx 2.7 \cdot 10^{-12} \text{ cm}^{-2} \text{ s}^{-1}$ at energies > 100 TeV and for a duration ≈ 5 hrs. The only significant positive sporadic excess is still the burst detected by the EAS-TOP, Baksan and KGF arrays on 23rd February 1989, for which the overall confidence level is $\approx 10^{-5}$.

Of some particular interest is the results of the search for a periodic signal (237 ms) from Geminga: the light curve shows a 3.4 s.d. excess in the bin corresponding to the EGRET higher peak. The associated probability for the effect to be simulated by a background fluctuation is $\approx 2 \cdot 10^{-3}$: being not compelling for the identification of a signal, an upper limit to the pulsed emission at the phases of the two pulsar peaks is: $\Phi (> 45 \text{ TeV}) < 1.2 \cdot 10^{-13} \text{ cm}^{-2} \text{ s}^{-1}$.

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APPENDIX A: Effective area and energy threshold

The array effective area $A(E)$ as a function of the primary gamma-ray energy E is calculated through a simulation which includes:

- the longitudinal e.m. cascade development in the atmosphere and its fluctuations;
- the lateral distribution function according to the Nishimura-Kamata-Greisen formalism [41], which fits the experimental data;
- the transition effect in the scintillators and their containers;
- the path of each source in the sky.

While for external events S_3 and S_4 , $A(E)$ is an increasing function of the energy, in the case of internal events S_1 and S_2 it saturates at a value A_0 (which is the effective area shown in tab.1). For each considered source $A_{\text{eff}} = A_0 / \cos \langle \vartheta \rangle_{\text{obs}}$ (see tab.3 for the values of $\langle \vartheta \rangle_{\text{obs}}$).

The energy threshold E_0 is then defined as:

(a) for internal events S_1 and S_2 :

$$\int_0^{\infty} E^{-\gamma} A(E) dE = A_{\text{eff}} \int_{E_0}^{\infty} E^{-\gamma} dE$$

being γ the differential index of the primary energy spectrum (we use $\gamma = 2.4$ for the Crab Nebula and $\gamma = 2$ for all the other sources);

(b) for external events S_3 and S_4 , as the mode of the distribution $A(E) \cdot E^{-\gamma}$ (for internal events E_0 is slightly higher than this value).

APPENDIX B: Flux calculations

The number of photons with energy $E > E_0$ detected from a point source with energy spectrum $bE^{-\gamma}$ is:

$$n_{\gamma}(>E_0) = \varepsilon T \int_{E_0}^{\infty} b E^{-\gamma} A(E) dE$$

where ε is the angular efficiency (see tab. 2 for its value for the different data sets) and T the total exposure time. If no excess is measured from the source, the limit to n_{γ} is:

$$n_{\gamma} < n_{\text{oss}}$$

where n_{oss} is the upper limit to the signal, corresponding to 90% confidence level, obtained following the method described in ref. [42].

The limit to the coefficient b of the source spectrum is therefore:

$$b < \frac{n_{\text{oss}}}{\varepsilon T \int_{E_0}^{\infty} E^{-\gamma} A(E) dE}$$

and hence to the flux:

$$\Phi_{\gamma}(>E_0) < \frac{n_{oss}}{\int_{E_0}^{\infty} E^{\gamma} A(E) dE} \frac{1}{\varepsilon T(\gamma - 1)} E_0^{\gamma+1}$$

For internal events, S_1 and S_2 , for which the effective area A_{eff} is defined (see appendix A), the expression of the upper limit is:

$$\Phi_{\gamma}(>E_0) < \frac{n_{oss}}{\varepsilon T A_{eff}}$$

REFERENCES

- [1] Nesphor Y.I. et al, *Astrophys. Space Sci.* 61 (1979) 349
- [2] Morello C. et al, *Proc. 18th Int. Cosmic Ray Conf.*, Bangalore, August 1983, 1, 137; Morello C. et al, *Il Nuovo Cimento* 13C (1990) 453
- [3] Samorsky M. and Stamm W., *Ap. J.* 268 (1983) L17
- [4] Lloyd-Evans J. et al, *Nature* 305 (1983) 784
- [5] Vacanti G. et al, *Ap. J.* 377 (1991) 467
- [6] Alexeenko V.V. et al, *J. Phys. G* 18 (1992) L83
- [7] Acharya M. et al, *Nature* 347 (1990) 364
- [8] Aglietta M. et al, *Europhysics Letts.* 15 (1991) 81
- [9] Bertsch D.L. et al, *Ap. J. Letts* 415 (1993) 113
- [10] Bertsch D.L. et al, *Nature* 357 (1992) 306
- [11] Bowden C.C.G. et al, *J. Phys. G* 19 (1993) L29
- [12] Vishwanath P.R. et al, *Astron. and Astrophys.* 267 (1993) L5
- [13] Akerlof C.W. et al, *Astron. and Astrophys.* 274 (1993) L17
- [14] Punch M. et al, *Nature* 358 (1992) 447
- [15] Aglietta M. et al, *Nucl. Instr. and Meth. in Phys. Res.* A277 (1988) 23
- [16] Aglietta M. et al, *Nucl. Instr. and Meth. in Phys. Res.* A336 (1993) 310
- [17] Aglietta M. et al, *Proc. 21st Int. Cosmic Ray Conf.*, Adelaide, January 1990, 2, 345
- [18] Aglietta M. et al, *Proc. 22nd Int. Cosmic Ray Conf.*, Dublin, August 1991, 1, 277
- [19] Aglietta M. et al, *Proc. 23rd Int. Cosmic Ray Conf.*, Calgary, August 1993, 1, 216
- [20] Aglietta M. et al, *Proc. 22nd Int. Cosmic Ray Conf.*, Dublin, August 1991, 1, 404
- [21] Aglietta M. et al, *Ap. J.* 397 (1992) 148
- [22] Alexandreas D.E. et al, *Ap. J.* 383 (1991) L53
- [23] Cronin J.W. et al, *Phys. Rev. D* 45 (1992) 4385
- [24] Amenomori M. et al, *Phys. Rev. Letts.* 69 (1992) 2468
- [25] Merck M. et al, *Proc. 23rd Int. Cosmic Ray Conf.*, Calgary, August 1993, 1, 361
- [26] Aglietta M. et al, *Proc. 22nd Int. Cosmic Ray Conf.*, Dublin, August 1991, 2, 708
- [27] Li T. and Ma Y., *Ap. J.* 272 (1983) 317
- [28] Forti C. et al, *Phys. Rev. D* 42 (1990) 3668

- [29] Aglietta M. et al, Proc. 23rd Int. Cosmic Ray Conf., Calgary, August 1993, 4, 247
- [30] Standish E.M., Astron. and Astrophys. 114 (1982) 297
- [31] Van Der Klis M. and Bonnet Bidaud J.M., Astron. and Astrophys. 214 (1989) 203
- [32] Johnston K., private communication, 1989
- [33] Lyne A.G. and Pritchard R.S., private communication, 1994
- [34] Morello C. et al, Il Nuovo Cimento 10C (1987) 142
- [35] Halpern J.P. and Holt S.S., Nature 357 (1992) 222
- [36] Halpern J.P. and Tytler, Ap.J. 330 (1988) 201
- [37] Mayer-Hasselwander H.A., IAU Circular n.5649, 1992
- [38] Mattox J. et al, 1994, Proc. of the 2nd Compton Gamma-Ray Observatory Symposium, College Park, MD, Sept. 20-22 1993, AIP, in press
- [39] Aglietta M. et al, Proc. 23rd Int. Cosmic Ray Conf., Calgary, August 1993, 1, 309
- [40] Dingus B.L. et al, Phys. Rev. Letts 61 (1988) 1906
- [41] Kamata K. et al, Prog. Theor. Phys. Suppl. 6 (1958) 93
- [42] Helene O., Nucl. Instr. and Meth. 212 (1982) 319

Epoch	Scintillator area [m ²]	Enclosed area (Effective area) [m ²]	trigger condition	trigger rate [Hz]
Feb. - Sep. 1989	240	8.0 10 ⁴ (4.2 10 ⁴)	seven-fold	6
Oct. 1989 - Dec. 1990 Nov. 1991 - Oct. 1992	290	1.0 10 ⁵ (5.0 10 ⁴)	four-fold	30
Nov. 1992 - present	350	1.5 10 ⁵ (6.7 10 ⁴)	four-fold	35

Table 1. The different configurations of the EAS-TOP array.

Events class	Internal (S ₁)	N _e >10 ⁵ (S ₂)	External high energy (S ₃)	External low energy (S ₄)
σ_{θ}	0.85°	0.5°	2.5°	5.6°
$\Delta\delta$	1.5°	0.8°	4.0°	4.0°
Angular efficiency (ϵ)	0.9	0.8	0.8	0.3
Sensitivity (a.u.)	0.5	1	0.5	0.04

Table 2. Characteristics of the different classes of events used in the present analysis.

Source	Min. zenith. distance	$\langle\vartheta\rangle_{\text{obs}}$	Daily exposure[hrs]	E_{th} [TeV]
Cygnus X-3	1.5°	20.3°	7.3	S ₁ : 90 S ₂ : 230 S ₃₊₄ : 25
Hercules X-1	7.1°	21.7°	6.9	S ₁ : 90 S ₂ : 240 S ₃₊₄ : 25
Cygnus X-1	7.2°	21.7°	7	S ₁ : 90 S ₂ : 230 S ₃₊₄ : 25
4U0115+6112	21.3°	28.5°	8.0	S ₁ : 120 S ₂ : 300 S ₃₊₄ : 25
Crab Nebula	20.4°	28.0°	5.5	S ₁ : 105 S ₂ : 280 S ₃₊₄ : 25
Geminga	24.7°	30.4°	5.0	S ₁ : 140 S ₂ : 350 S ₃₊₄ : 40
PSR1953+29	13.3°	24.2°	6.3	S ₁ : 100 S ₂ : 260 S ₃₊₄ : 25
PSR1937+214	20.9°	28.1°	5.5	S ₁ : 120 S ₂ : 300 S ₃₊₄ : 25
PSR 0157+6112	19.9°	27.7°	8	S ₁ : 120 S ₂ : 300 S ₃₊₄ : 25
LSI+61	18.7°	27.1°	8	S ₁ : 120 S ₂ : 300 S ₃₊₄ : 25
North Gal. Pole	15.3°	25.2°	6	S ₁ : 100 S ₂ : 260 S ₃₊₄ : 25
M31	1.2°	20.3°	7.3	S ₁ : 90 S ₂ : 240 S ₃₊₄ : 25
Markarian 421	4.3°	21.0°	7	S ₁ : 90 S ₂ : 240 S ₃₊₄ : 25

Table 3. List of the candidate sources and of their observation parameters.

Year (N_{days})	E_{th} [TeV]	N_{ON}	N_{OFF}	S	Φ (d.c.) [$\text{cm}^{-2} \text{s}^{-1}$]	Φ (puls) [$\text{cm}^{-2} \text{s}^{-1}$]
1989 (104)	25	239146	239483	-0.6	$1.3 \cdot 10^{-12}$	$2.0 \cdot 10^{-13}$
	90	5727	5705	+0.3	$2.9 \cdot 10^{-13}$	$4.5 \cdot 10^{-14}$
	230	168	160	+0.6	$1.6 \cdot 10^{-13}$	$2.5 \cdot 10^{-14}$
1990 (248)	25	2614813	2615858	-0.6	$8.3 \cdot 10^{-13}$	$1.3 \cdot 10^{-13}$
	90	24457	24778	-1.9	$5.3 \cdot 10^{-14}$	$8.3 \cdot 10^{-15}$
	230	1230	1190	+1.1	$3.7 \cdot 10^{-14}$	$5.8 \cdot 10^{-15}$
1992 (225)	25	1787252	1786923	+0.2	$1.3 \cdot 10^{-12}$	$2.0 \cdot 10^{-13}$
	90	19782	19512	+1.8	$2.1 \cdot 10^{-13}$	$3.3 \cdot 10^{-14}$
	230	1113	1112	+0.	$3.1 \cdot 10^{-14}$	$4.9 \cdot 10^{-15}$
1993 (209)	25	2323078	2324199	-0.7	$9.0 \cdot 10^{-13}$	$1.4 \cdot 10^{-13}$
	90	25391	25547	-0.9	$6.5 \cdot 10^{-14}$	$1.0 \cdot 10^{-14}$
	230	1713	1686	+0.6	$2.9 \cdot 10^{-14}$	$4.5 \cdot 10^{-15}$
all (786)	25	6964289	6966463	-0.8	$4.5 \cdot 10^{-13}$	$7.1 \cdot 10^{-14}$
	90	75357	75542	-0.6	$4.1 \cdot 10^{-14}$	$6.4 \cdot 10^{-15}$
	230	4224	4148	+1.1	$2.0 \cdot 10^{-14}$	$3.2 \cdot 10^{-15}$

Table 4. Cygnus X-3: number of events from the source (col.3), from the background (col.4), significance of the excess above the background (col.5), 90% confidence level upper limits to the d.c. (col.6) and periodic flux (col.7).

E_{th} [TeV]	S_{max} [s.d.]	Expected number of events	Φ_s [$\text{cm}^{-2} \text{s}^{-1}$]
20	3.8	0.1	$1.4 \cdot 10^{-11}$
90	2.9	1.5	$2.3 \cdot 10^{-12}$
170	3.7	0.1	$8.3 \cdot 10^{-13}$

Table 5. Cygnus X-3: maximum excesses recorded in $N_d=786$ days of measurements for each data-set, number of events with significance $> S_{\text{max}}$ expected in N_d days and the 90% confidence level upper limits to a sporadic emission lasting ≤ 7 hours.

N_{days}	E_{th} [TeV]	N_{ON}	$N_{\langle \text{OFF} \rangle}$	S	Φ (d.c.)	Φ (puls)
816	25	3813499	3813856	-0.2	$4.7 \cdot 10^{-13}$	$8.2 \cdot 10^{-14}$
	105	41699	41364	+1.5	$9.0 \cdot 10^{-14}$	$1.6 \cdot 10^{-14}$
	280	2563	2543	+0.4	$1.6 \cdot 10^{-14}$	$2.8 \cdot 10^{-15}$

Table 6. Crab Nebula and Pulsar: summary of the results obtained in the search for d.c. and pulsed emission (see the caption of tab. 3).

E_{th} [TeV]	S_{max} [s.d.]	Expected number of events	Φ_s [cm ⁻² s ⁻¹]
25	2.6	3.8	$2.1 \cdot 10^{-11}$
105	3.2	0.6	$2.7 \cdot 10^{-12}$
225	3.2	0.6	$7.7 \cdot 10^{-13}$

Table 7. Crab Nebula: maximum recorded excesses in $N_d=816$ days of measurements for each data-set, number of events with significance $> S_{\text{max}}$ expected in N_d days and the 90% confidence level upper limits to a sporadic emission lasting ≤ 5.5 hours.

Array	Time (UT)	ON	$\langle \text{OFF} \rangle$	S
Baksan	13-16	55	34.1	3.1
KGF	15-18	35	17.8	3.4
EAS-TOP (S_1)	17-20	38	25.5	2.1
" (S_3)	"	403	378.3	1.2

Table 8. Summary of the observations of the Crab Nebula on the 23rd February 1989, by the Baksan, KGF and EAS-TOP arrays.

N_{days}	E_{th} [TeV]	N_{ON}	$N_{\langle \text{OFF} \rangle}$	S	Φ (d.c.)
811	40	2864546	2863202	+0.7	$6.6 \cdot 10^{-13}$
	140	30948	30969	-0.1	$5.0 \cdot 10^{-14}$
	350	1319	1310	+0.2	$1.8 \cdot 10^{-14}$

Table 9. Geminga: summary of the d.c. data for the complete database (1989-1993).

E_{th} [TeV]	N_{ON}	$N_{\langle \text{OFF} \rangle}$	S
30	586783	586724	+0.1
45	1045655	1043798	+1.7
130	19128	19051	+0.5
175	1319	1311	+0.2

Table 10. Geminga: summary of the d.c. data collected in 1992 and 1993.

E_{th} [TeV]	S_{max}	Expected number of events	Φ_s [$\text{cm}^{-2} \text{s}^{-1}$]
40	3.2	0.6	$1.0 \cdot 10^{-11}$
130	2.7	2.8	$2.3 \cdot 10^{-12}$
175	2.8	2.1	$6.5 \cdot 10^{-13}$

Table 11. Geminga: maximum recorded excesses in $N_d=811$ days of measurements for each data-set, number of events with significance $> S_{\text{max}}$ expected in N_d days and the 90% confidence level upper limits to a sporadic emission lasting ≤ 5.5 hours.

Source (Ndays)	E_{th} [TeV]	N_{ON}	$N_{\langle OFF \rangle}$	S	Φ (d.c.) [$10^{-14} \text{ cm}^{-2} \text{ s}^{-1}$]
Hercules	25	6382512	6387242	-1.7	2.8
X-1	90	69515	69312	+0.7	6.8
(800)	240	4025	3967	+0.9	1.9
Cygnus	25	3711293	3712610	-0.6	4.9
X-1	90	40473	40733	-1.2	4.2
(437)	240	2629	2607	+0.4	1.9
4U0	25	5280196	5273043	+2.9	11.0
115+6112	120	54801	54682	+0.5	5.5
(738)	300	1811	1780	+0.7	1.7
PSR	25	5222050	5224898	-1.2	3.4
1953+29	100	56695	56812	-0.5	4.5
(800)	260	2228	2215	+0.3	1.9
PSR	25	3659668	3662983	-1.6	2.9
1937+214	120	39614	39814	-0.9	3.7
(810)	300	1622	1630	-0.2	1.6
PSR	25	3213713	3211822	+1.0	8.1
0157+6112	120	34104	34101	+0.02	5.8
(408)	300	1981	1919	+1.3	2.2
LSI+61	25	3345589	3345253	+0.2	6.1
	120	35673	35676	-0.01	5.8
(410)	300	1978	2010	-0.7	1.1
North Gal.	25	4882259	4881099	+0.5	6.9
Pole	100	52896	52719	+0.7	6.9
(808)	260	2120	2156	-0.7	1.3
M31	25	7021155	7024759	-1.3	3.2
	90	75467	75922	-1.5	3.0
(780)	230	2714	2776	-1.1	1.1
Markarian	25	3996585	4002534	-2.8	2.6
421	90	43654	43903	-1.1	4.4
(441)	240	2770	2841	-1.2	1.1

Table 12. Results obtained in the search for d.c. emission through the complete database (1989-1993) from the 10 candidate sources.

Source	E_{th} [TeV]	S_{max} [s.d.]	Expected number of events	Φ_s [cm ⁻² s ⁻¹]
Hercules X-1	25	3.0	1.0	1.2 10 ⁻¹¹
	90	3.3	0.4	2.7 10 ⁻¹²
	240	2.9	1.5	6.7 10 ⁻¹³
Cygnus X-1	25	2.3	4.7	8.1 10 ⁻¹²
	90	2.7	1.5	2.0 10 ⁻¹²
	240	2.8	1.1	6.0 10 ⁻¹³
4U0 115+6112	25	3.3	0.4	1.2 10 ⁻¹¹
	120	2.9	1.4	2.0 10 ⁻¹²
	300	3.6	0.1	6.1 10 ⁻¹³
PSR 1953+29	25	2.8	2.1	1.1 10 ⁻¹¹
	100	2.9	1.5	2.4 10 ⁻¹²
	260	2.7	2.8	6.1 10 ⁻¹³
PSR 1937+214	25	3.5	0.2	1.6 10 ⁻¹¹
	120	4.5	0.01	3.7 10 ⁻¹²
	300	3.4	0.3	7.8 10 ⁻¹³
PSR 0157+6112	25	3.2	0.3	1.1 10 ⁻¹¹
	120	2.7	1.4	1.8 10 ⁻¹²
	300	2.9	0.8	5.1 10 ⁻¹³
LSI+61	25	2.6	1.9	9.4 10 ⁻¹²
	120	2.3	4.4	1.6 10 ⁻¹²
	300	2.6	1.9	4.6 10 ⁻¹³
North Gal. Pole	25	3.3	0.4	1.3 10 ⁻¹¹
	100	2.9	1.5	2.4 10 ⁻¹²
	260	3.5	0.2	8.1 10 ⁻¹³
M31	25	2.6	3.7	9.8 10 ⁻¹²
	90	3.5	0.2	2.9 10 ⁻¹²
	230	2.6	3.7	5.5 10 ⁻¹³
Markarian 421	25	3.7	0.1	1.3 10 ⁻¹¹
	90	3.3	0.2	2.6 10 ⁻¹²
	240	2.7	1.5	6.0 10 ⁻¹³

Table 13. Maximum recorded excesses in the total period of measurement, the expected number of events with significance $> S_{max}$ and the 90% upper limits to sporadic emission for 10 candidate sources (the duration of such emission is shown in table 3 for each source)

1. Schematic view of the full EAS-TOP array.

2. The angular resolution
as a function of EAS electron size N_e .

3. Percentage deficit of events vs. the angular distance from the center of the Moon: (a) 1990 data, (b) 1992 data, (c) 1993 data, (d) total data set.

4. Cygnus X-3 light curve, obtained from internal events for the total exposure time.

5. Distribution of daily excesses for S_1 events from the direction of Cygnus X-3. The expectation from a Gaussian distribution is also shown.

6. Crab Pulsar light curve, (a): S_1 events, (b): S_2 events.

7. Distribution of the daily excesses of the S_1 events from the direction of the Crab Nebula. Expectation from a Gaussian distribution is also shown. The arrow indicates the burst of 23 February 1989.

8. Geminga Pulsar light curve. Phases corresponding to peak 1 (P1) and 2 (P2) of "EGRET" emission are indicated.

9. Distribution of the daily excesses of the events from the direction of Geminga. Expectation from a Gaussian distribution is also shown.

10. Distribution of the daily significances of the events from the direction of Hercules X-1. Expectation from a Gaussian distribution is also shown.