Search for $\approx 10^{14}$ eV γ-ray sources from a full sky survey at EAS-TOP

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Abstract

Different studies in the field of ultra-high energy γ ray astronomy have been performed by the EAS-TOP extensive air shower array, through a survey of the northern sky ($19° < \delta < 69°$) at primary energies $E_1 \approx 30$ TeV and $E_2 \approx 100$ TeV. The obtained results are discussed in connection with different problems of cosmic ray acceleration, such as γ-ray bursts, supernova remnants, extremely high energy events.

1 Introduction:

Gamma-ray astronomy at ultra-high energy (UHE, i.e. $\approx$ 100 TeV) is potentially a powerful tool for different investigations related to problems of astro-particle physics and to the origin of high energy cosmic rays. As important topics we remind: a) the spectrum of the sources detected by satellites or atmospheric Cherenkov technique (ACT) (e.g. Crab Nebula, AGNs), related on one hand to the capability of such objects to accelerate particles up to the highest energies and on the other to gamma-ray absorption on low energy photons in the intergalactic space and hence to their density; b) the possibility to check the particle acceleration by supernova remnants (SNRs) and the expected energy cutoff; c) the diffuse emission from the Galaxy and therefore the cosmic ray distribution in it; d) the possibility of particle acceleration connected to γ-ray bursts (GRBs); e) the study of possible γ-ray emission correlated to EHE ($E_0 > 4 \cdot 10^{19}$ eV) cosmic rays.

We will summarize here the results of the EAS-TOP array related to some cosmic ray acceleration processes connected to GRBs (i.e. unpredictable sources), SNRs, EHE events clustering directions.

2 The EAS-TOP array:

EAS-TOP is an extensive air shower array located in central Italy, at Campo Imperatore (2005 m a.s.l., National Gran Sasso Laboratories, lat. 42.5° N, long. 13.5° E). The detector of the electromagnetic component (Aglietta et al., 1988, 1993), fully operational since 1992, consists of 35 modules of scintillator 10 m^2 each, spread over an area $A \approx 10^5$ m^2. Different selection criteria based on the number of triggered scintillators, core location, angular resolution, are applied to the data in order to investigate different primary energies. In the present analysis we use (i) showers with at least 4 fired modules, without core location (Low Energy, L.E. events, trigger rate $\nu \approx 20$ Hz), and (ii) showers with at least 7 fired modules and core located inside the edges of the array (High Energy, H.E. events, trigger rate $\nu \approx 2$ Hz). The angular resolutions are respectively $\sigma_\theta = 2.5°$ (taking into account the uncertainty in core location) and $\sigma_\theta = 0.83° \pm 0.10°$, obtained through the measurement of the shape of the Moon shadow on the flux of primary c.r. (Aglietta et al., 1991), thus including systematic effects. The typical triggering primary energies are $E_{typ}^{L.E.} \approx 25$ and $E_{typ}^{H.E.} \approx 90$ TeV, in the angular window $\theta < 40°$.

3 Analysis technique:

The basis of the survey technique is, for each sidereal day, a 1°× 1° map in celestial coordinates of the arrival directions of showers with zenith angle θ <40°.

All-sky survey. 1°× 1° cells are grouped so to tile the visible sky with a set of approximately equal solid angle bins, whose dimensions are optimized on the angular resolution. In these secondary maps, for H.E. (L.E.) events, bin centers are spaced by $\Delta\delta$ =4° (8)° in declination, and by $\Delta\alpha$ =4° (8)° - 6° (12)° - 8° (18)° in right ascension, depending on δ. In order to lessen edge effects, four different series of overlapping maps (M_1, M_2, M_3, M_4) are produced for each trigger condition, the bins centers being shifted with respect to M_1: for M_2 of ($\delta_s = \Delta\delta/2, \alpha_s = 0$), for M_3 of ($\delta_s = 0, \alpha_s = \Delta\alpha/2$), for M_4 of ($\delta_s = \Delta\delta/2, \alpha_s = \Delta\alpha/2$). Due to such overlapping, under the most favorable condition (i.e. the source is in the center of a bin) the angular efficiency ϵ is 0.98 (0.7) for H.E (L.E.) data set, while in the most unfavorable condition ϵ = 0.7 (0.5). In the case of H.E. (L.E.) events, the observed intervals of declination are 19° $< \delta <$ 67° (17° $< \delta <$ 65°) for M_1 and M_3, and 21° $< \delta <$ 69° for M_2 and M_4, corresponding to 12 (6) declination bands and 780 (190) cells for each serie of maps. The search is performed by means of the ON-OFF technique: each bin of the map is considered as a potential γ-ray source and its number of counts (N_{on}) is compared with the number of counts (N_{off}) from 6 adjacent cells located in the same declination band and next to the on-source bin. For each of them the significance S of the observed excess ($N_{on} - < N_{off} >$) is computed (Li & Ma, 1983).

Candidate sources are searched in bins of dimensions $\Delta\delta$ = 1.58 σ_θ and $\Delta\alpha = \Delta\delta/cos\delta$ (bin sizes for the extended SNRs, such as HB21 and Monoceros, are enlarged to preserve the same angular efficiency as for point sources). The ON-OFF technique is then applied.

The EAS-TOP data from January 1st, 1992, to May 31th, 1998, (1433 days of observation) have been used for the analysis.

4 Results and Interpretation:

4.1 All-sky survey: A search for short duration transients (Δt< 1 s) has been performed in the energy ranges E_γ > 10 GeV and E_γ > 80 TeV (Aglietta et al., 1996).

Moreover, γ-ray bursts could be accompanied by the acceleration of EHE cosmic rays (Vietri, 1997) and hence by UHE γ-rays which, interacting with the cosmic background photons, would pile up at $E_\gamma \approx$ 100 TeV, possibly with time distributions longer than those of their lower energy counterparts. We have thus performed an all-sky survey searching for unexpected sources: D.C. and transient emissions have been studied (for the latter the natural integration time of one source transit has been chosen).

D.C. emission: for each cell, integrating the number of counts over all the observation time, the significance S of the observed excess has been calculated. Both for H.E. and L.E. events, the obtained S distributions are consistent with zero mean and unit-width gaussians: no candidate sources are found in either the H.E. or L.E. events data set. For a source culminating at the zenith, the resulting 90% c.l. upper limits to D.C. flux, assuming a spectral index γ=2, are: $\Phi(>$25 TeV) < 4.3· 10^{-13} cm^{-2} s^{-1}, $\Phi(>$90 TeV) < 9.2· 10^{-14} cm^{-2} s^{-1} (for details of limit calculations see Ghia et al., 1999).

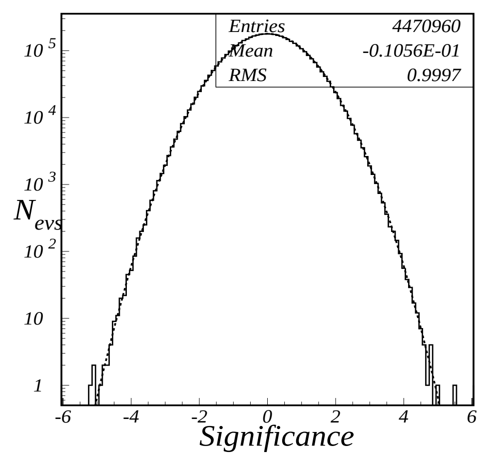

Figure 1: *Transients search: distribution of daily significances of observed H.E. excesses in each cell. A unit-width and zero mean gaussian is superimposed.*

Transients: the distribution of significances of the excesses observed in each cell for each daily transit is shown in Fig. 1 for H.E. events: it is compatible with a unit-width and zero mean gaussian (shown in the same figure, χ^2_ν = 1.5). The chance imitation rate corresponding to the most significant excess (S=5.5) is $N_{exp} = 0.08$:

all excesses are consistent with poissonian background fluctuations. Since a similar statistical behaviour is observed also for L.E. triggers, we conclude that, at 90% c.l., <0.6 events/yr have been detected with duration Δt$<$ 8 hrs and $\Phi(>$25 TeV)$>$ 1.8$\cdot 10^{-11}$ cm^{-2} s^{-1}, $\Phi(>$90 TeV)$>$ 5.1$\cdot$ 10^{-12} cm^{-2} s^{-1}, for a source culminating at the zenith of the visible sky.

4.2 Supernova Remnants: Under the accepted hypothesis that galactic cosmic rays with energy less than $\approx$ 100 TeV are accelerated in shock waves in shell-type supernovae remnants, measurements on accompanying UHE γ-rays could provide information both on the acceleration mechanisms and on the expected energy cutoff. H.E and L.E. EAS-TOP data sets have been searched for emission from seven SNRs: the EGRET data from their direction (Esposito et al., 1996) were analyzed and for three of them (i.e. γ Cyg, IC443 and Monoceros) a correlation with enhanced γ-ray emission was found.

Source	Daily exp. [h]	Diam. [°]	E$_{typ}$ [TeV]	N$_{evs}$	S$_{d.c.}$	$\Phi_{d.c.}$ [cm^{-2} s^{-1}]
W51	5	0.5	40	$4.2\cdot10^{6}$	-0.6	$1.2\cdot 10^{-13}$
γ Cyg	8	1	25	$1.6\cdot10^{7}$	+0.5	$1.7\cdot 10^{-13}$
W63	8.5	1.3	25	$2.0\cdot10^{7}$	+0.8	$2.0\cdot 10^{-13}$
HB21	8.5	2	25	$1.7\cdot10^{7}$	+0.7	$1.8\cdot 10^{-13}$
Cas A	9	0.1	25	$1.4\cdot10^{7}$	-0.7	$1.3\cdot 10^{-13}$
IC 443	6.5	0.75	25	$8.4\cdot10^{6}$	-1.3	$1.5\cdot 10^{-13}$
Monoceros	3.5	3.7	40	$3.1\cdot10^{6}$	-1.2	$2.5\cdot 10^{-13}$

Table 1: *Summary of the search for d.c. emission from SNRs: for each of them the diameter, daily exposure, typical primary energy, number of ON source events, d.c. excess significances, 90% c.l. upper limits to the d.c. flux are given.*

Results of the observations are shown in Table 1: none of the remnants shows evidence for γ-ray emission. Flux upper limits at 90% c.l. are derived (for their calculation see Aglietta et al., 1995). For γ Cyg, IC443 and Monoceros they are compared with lower energy fluxes as measured by EGRET: concerning the first two, an extrapolation of the EGRET differential γ-ray flux $\propto$ E^{-2} is excluded, indicating a steeper spectrum ($\gamma >$ 2.2) or a spectral cutoff (consistent with Whipple result, Buckley et al., 1998). With regards to Monoceros (not studied by ACT detectors due to its extended dimension), the extrapolation up to 40 TeV of the EGRET spectral index $\gamma \approx$ 1.69 (Jaffe et al., 1997) can be excluded, and a limit $\gamma >$ 2.1 is obtained.

4.3 EHE clusters of events: 47 EHE cosmic rays above 4$\cdot$ 10^{19} eV (i.e. GKZ cutoff) have been observed by the AGASA experiment (Takeda et al., 1999); 9 of them are clustered into one triplet and three doublets. The corresponding directions have been searched for UHE γ-ray emission in the EAS-TOP data.

Source	E$_{typ}$ [TeV]	N$_{ON}$	N$_{\langle OFF\rangle}$	S	$\Phi_{d.c.}$ [cm^{-2} s^{-1}]
doublet (a)	25	8481683	8478596	+1.0	$2.6\cdot 10^{-13}$
$<\delta>$=20.6°, $<\alpha>$=18.6°	120	202364	203041	-1.4	$4.2\cdot 10^{-14}$
doublet (b)	25	15684665	15684431	+0.1	$1.4\cdot 10^{-13}$
$<\delta>$=48.1°, $<\alpha>$=283.°	90	301275	301750	-0.8	$3.3\cdot 10^{-14}$
doublet (c)	25	12364070	12357264	+1.8	$2.6\cdot 10^{-13}$
$<\delta>$=30.0°, $<\alpha>$=69.9°	100	192058	191307	+1.6	$5.8\cdot 10^{-14}$
triplet	25	14562977	14570775	-1.9	$1.1\cdot 10^{-13}$
$<\delta>$=56.9°, $<\alpha>$=169.7°	100	334472	334471	0.	$4.0\cdot 10^{-14}$
Σ	25	51093396	51091068	+0.3	$8.5\cdot 10^{-14}$
	100	1030169	1030569	-0.4	$1.9\cdot 10^{-14}$

Table 2: *Summary of the search for emission from EHE clusters: coordinates, typical primary energies, number of observed events on- and off-source, d.c. excess significances, 90% c.l. upper limits to the d.c. flux are given.*

As shown in Table 2 (where the mean directions are given), from none of them a significant excess is observed: 90% c.l. upper limits to the flux are given for each observed position. The data and upper limit, Φ_{Σ}, relative to the sum of the four of them are also shown.

The lack of a γ-ray signal at UHE provides constraints to the mechanisms of acceleration of EHE cosmic rays, both in the frame of "bottom-up" models and of "top-down" ones.

Concerning the latter, we consider the model of Blasi, 1999, in which the flux of UHE γ-rays is calculated from the decay of super-heavy relic particles clustered in the galactic halo. If these particles cluster at the positions corresponding to the arrival directions of c.r. with energy $>$ 4$\cdot$ 10^{19} eV, the diffuse intensity I_γ evaluated by Blasi (see Fig. 2) would be concentrated in point-like γ-ray sources. We convert the upper limit Φ_Σ to I_γ through expression: $I_\gamma = \Phi_\Sigma \cdot \frac{1}{4\pi} \cdot \frac{9}{47}$ cm^{-2} s^{-1} sr^{-1}. The limit obtained through L.E. triggers (not affected by absorption on low energy photons in space) is shown in Fig. 2. In this frame, X-masses m_X $>10^{14}$ GeV are excluded for ordinary QCD fragmentation function in hadrons production.

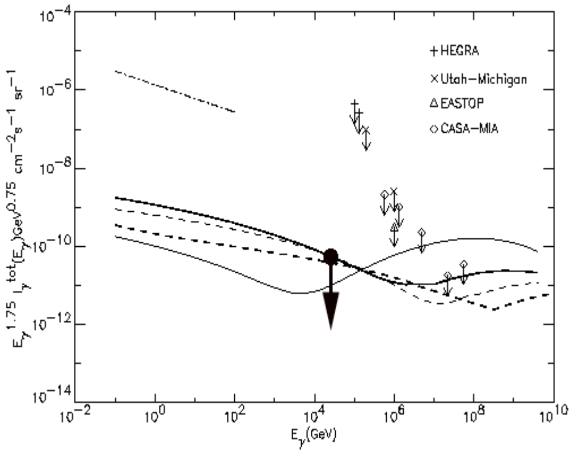

Figure 2: *Expected intensity of γ-rays from Blasi, 1999, for m_X =10^{14} GeV (thick lines) and m_X =10^{13} GeV (thin lines). The solid lines refer to SUSY-QCD fragmentation function and the dashed lines to ordinary QCD one. Crosses, triangles and diamonds indicate experimental upper limits to diffuse emission. Full dot and arrow represent the result of the present analysis.*

Concerning conventional EHE c.r. acceleration, the clustering effect suggests the possibility of " nearby" sources (D <30 Mpc) (Medina Tanco, 1999). The γ-ray flux due to the interaction of c.r. with matter has been considered by different authors. In general at E_0 $\approx$ 100 TeV: $\frac{I_\gamma}{I_p} \approx 6\cdot 10^{-4} \times x$ (g cm^{-2}) (x = absorber thickness) (Gaisser et al., 1991) (1). For our case, using as I_p the extrapolation back to $\approx$ 100 TeV of the suggested power law spectrum (γ=3), for the 3 events (over 47) of the AGASA triplet, from the limit of Tab. 2 we obtain $\frac{I_\gamma}{I_p} < 3.3\cdot 10^{-7}$, i.e. comparing with expression (1), $x^{source}_{matter} < 5\cdot 10^{-4}$ g cm^{-2}. Concerning photons, from π_0 photoproduction we obtain: $x^{source}_{photon} < 1.5\cdot 10^{23}$ ph cm^{-2} for $E_{ph} \approx$ KeV.

These upper limits on matter and X-ray photons column densities set significant constraints on the characteristics of the proposed sources.

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