Search for $\approx 10^{14}$ eV γ-ray transients through the BAKSAN and EAS-TOP correlated data

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Abstract

A search for transient point sources of ultra-high energy (U.H.E.) γ-rays has been performed, through the correlated data of BAKSAN and EAS-TOP Extensive Air Shower (EAS) arrays, which are located at very similar latitudes ($\approx$ 43° N), and separated of $\approx$ 33.7° in longitude. The search has been performed all over the observable sky (19° $< \delta <$69°), and from three candidate sources (Crab Nebula, Markarian 421 and Markarian 501) on timescales of a single source transit (i.e. $\approx$ 7 hrs), at typical primary energy $E_\gamma \approx 5 \cdot 10^{13}$ eV. A coincident episode from Markarian 421, observed on 15th January, 1994, with expected chance imitation rate n_{ch} =0.01 is discussed.

1 Introduction:

At TeV energies, experiments using the Atmospheric Cherenkov Technique (ACT) have successfully detected galactic - i.e. Crab Nebula (e.g. Weekes et al., 1989, Goret et al., 1993, Baillon et al., 1993, Tanimori et al., 1998) up to $E_\gamma \approx 5 \cdot 10^{13}$ eV - and extragalactic - e.g. the AGNs Markarian 421 (Mrk 421) (Punch et al., 1992), Markarian 501 (Mrk 501) (Quinn et al., 1996) - γ-ray sources. As at satellite energies (Von Montigny et al., 1995), AGNs are characterized by intense sporadic activity superimposing over d.c. fluxes (Buckley et al., 1996, Gaidos et al., 1996, Catanese et al., 1997, Protheroe et al., 1998).

At U.H.E. the most significant effect reported up to now concerns the outburst observed on February 23, 1989 from the Crab Nebula by the BAKSAN, Kolar Gold Field and EAS-TOP arrays (Alexeenko et al., 1992, Acharya et al., 1990, Aglietta et al., 1991). The combined chance imitation rate for the observation is $3 \cdot 10^{-4}$ and the flux is $\Phi_\gamma(>2 \cdot 10^{14}$ eV)=$(2 \pm 1) \cdot 10^{-12}$ cm^{-2} s^{-1}, i.e. about 100 times higher than the extrapolated flux from the ACT data.

Cosmic gamma-ray bursts could also be accompanied by the acceleration of extremely high energy particles (Vietri, 1997), and therefore by gamma rays of comparable energy (although with unpredictable time distribution), which would be attenuated by the interactions with the CMBR photons, while the produced radiation would pile-up at energies $E_\gamma \approx 10^{14}$ eV.

The search for γ-ray transients at $E_\gamma \approx 10^{14}$ eV can thus be significant, concerning both known and unknown sources. Moreover, EAS arrays are characterized by very high duty cycles and long operation times, and can thus be informative with respect to the ACT, in spite of their worse resolution and sensitivity. On the other hand, the establishment of sporadic effects is quite hard with a single detector, due to cosmic rays background, various sources of noise and the required long exposure times.

We have therefore performed a systematic search for possible coincident excesses in the BAKSAN and EAS-TOP Extensive Air Shower arrays data. The effective energy range of the two arrays is nearly the same due to the similarities of detectors dimensions, spacings, and altitudes: $E_\gamma \approx 5{\cdot}10^{13}$ eV, EAS-TOP being more sensitive due to its larger collecting area. Their locations on the Earth (latitudes respectively 43.3° N and 42.5° N, and longitudes 42.7° E and 13.5° E), together with their fields of view $\approx$ 40°, provide a superposition of about 5 hours for a source culminating at their zenith, the time shift being $\approx$ 2 hours. The coincident experiment, performed on the time basis of a single source transit, is sensitive to "fast" transient phenomena covering the observed variability range of Mrk 421 and Mrk 501. The data taking of the two arrays is superimposed for 474 days between 1992 and 1995. The correlated search has been performed over the full sky in cells of dimensions 4x4°, compatible with the angular resolution of both detectors, and for three candidate sources, i.e. Crab Nebula, Mrk 421 and Mrk 501.

2 The arrays:

2.1 The BAKSAN array: The BAKSAN Air Shower Array is located in southern Russia, in the North Caucasus region (1860 m a.s.l., Baksan Neutrino Observatory). The array (Alexeenko et al., 1987) consists of a large central scintillator detector (made of 400 liquid scintillator units, total area 200 m^2) surrounded by 6 smaller ones (each made of 18 units, 9 m^2 each). The array has a counting rate $\nu \approx 1$ Hz, the trigger being provided by the fourfold coincidence of the detectors nearest the central one (30 m from the center). For the sixfold coincidences of the external detectors, used in the present analysis, the angular resolution is $\sigma_\theta \approx$ 1.5°. The typical triggering primary energy in the angular window $\theta \leq$40° is $E_0 \approx 5{\cdot}\, 10^{13}$ eV for a source culminating at the zenith.

2.2 The EAS-TOP array: The EAS-TOP detector is located in central Italy, at Campo Imperatore (2005 m a.s.l., National Gran Sasso Laboratories). The detector of the electromagnetic component (Aglietta et al., 1988, 1993) 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 events with at least 4 fired modules, without core location, with trigger rate $\nu \approx$20 Hz. For these events the angular resolution is $\sigma_\theta = 2.5°$ (taking into account the uncertainty in core location). The typical triggering primary energy in the angular window $\theta \leq$40° is $E_0 \approx 3{\cdot}10^{13}$ eV for a source culminating at the zenith.

3 The analysis:

3.1 Full sky survey: The basis of the all-sky survey is a daily map in celestial coordinates of the arrival directions of all showers. Using events with zenith angle $\theta <$40°, the maps are produced by tiling the visible sky with a set of approximately equal solid angle bins. Bin centers are spaced by $\Delta\delta =$4° in declination, and by $\Delta\alpha =$4°$-$6°$-8°$ 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, 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 $(\delta_s = \Delta\delta/2, \alpha_s = \Delta\alpha/2)$. The observed intervals of declination are 19° $< \delta <$67° (M_1 and M_3) and $21° < \delta < 69°$ (M_2 and M_4), corresponding to 12 declination bands.

The search is performed by means of the ON-OFF technique: each bin of the map is considered as a potential γ-ray source (ON) 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 potential source the significance S of the observed excess ($N_{on} - < N_{off} >$) is computed (Li & Ma, 1983).

3.2 Candidate sources search: In the case of known sources the same ON-OFF technique is applied, where the ON bin is centered on the source position. For EAS-TOP the dimensions of the bins are $\Delta\delta =$ 1.58

σ_θ and $\Delta\alpha = \Delta\delta/cos\delta$, with $\Delta\delta$ =4° (angular efficiency ϵ=0.7). For Baksan, the cell dimensions are the same used in the all-sky survey (ϵ=0.7). Only days in which all ON and OFF cells are observed without interruptions up to the zenith angle $\theta = 40°$ are used for the analysis.

4 All-Sky search results:

4.1 Individual analysis: As a first step, the daily maps from each experiment relative to common days are analyzed. The distributions of significances S are shown in Fig. 1 for EAS-TOP (780$\times$ 4 cells $\times$ 474 days), and in Fig. 2 for Baksan (780$\times$ 4 cells $\times$ 424 days): both of them are consistent with normal ones with zero mean and unit standard deviation (the reduced chi-square χ^2_ν are respectively 1.1 and 1.8). The most significant observed excess is in the EAS-TOP data set (S=5.1). Being the number of trials N_{tr} =780$\times$ 4$\times$ 474, the expected number of such excesses is $N_{exp} = P(\geq 5.1) \times N_{tr}$ =0.25. The poissonian behaviour of the experimental fluctuations confirms the good stability and reliability of both detectors.

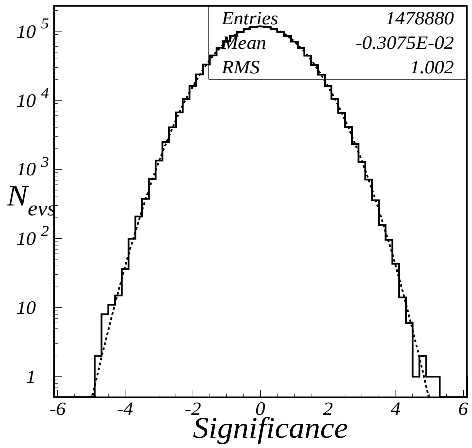

Figure 1: *EAS-TOP: daily significances of observed excesses in each cell.*

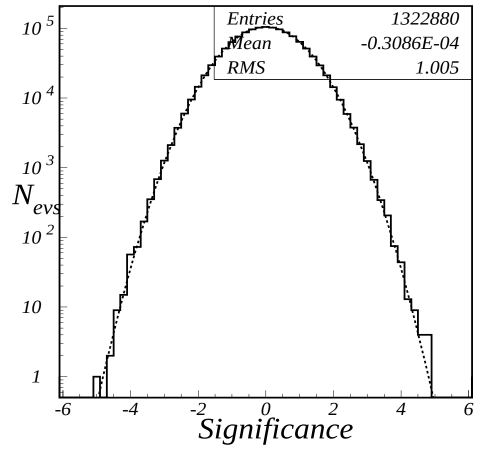

Figure 2: *Baksan: daily significances of observed excesses in each cell.*

4.2 Combined analysis: The absence of significant statistical excesses recorded by single installations do not preclude the possibility of positive results when combining the two detectors. Positive tails (and negative ones, as a consistency check) of the distributions are analyzed by selecting the n_{most} largest positive and negative excesses both in BAKSAN and EAS-TOP data sets: n_{most} =1, 3, 10, 30... Among them, coincidences in position and time are searched. The number of measured coincidences, C_{mea}, is compared with the expected one, C_{exp}, from chance rate. C_{exp} and C_{mea} (both for positive and negative tails) are compared in Fig. 3 (results for low values of n_{most}, representing the most significant region for the search of coincidences are given in the table on the same figure): no excess is observed above the chance rate.

5 Candidate sources search results:

Crab Nebula, Mrk 421 and Mrk 501, which are detected at VHE energies, have been studied. The distributions of their daily significances in the individual EAS-TOP and BAKSAN data sets are consistent with zero mean and unit width gaussians: no unexpected excess is found in both of them and in the combined analysis.

Concerning Mrk 421 (349 common days of observation) a correlated plot of daily significances corresponding to positive excesses observed in both experiments (S_{ET} and S_{BA}) is shown in Fig. 4. A single event (occurred on 15th January, 1994) corresponding to S_{ET}=2.6 S_{BA}=2.5, is at the edge of both distributions and the expected chance imitation rate is $n_{ch} = 0.01$.

6 Conclusions:

A search for possible transient gamma-ray sources at $E_0 \approx 3 \cdot 10^{13} \div 10^{14}$ eV has been performed through the Baksan and EAS-TOP data. No excess has been observed from a full sky survey over the visible sky: at

90% c.l., < 1.8 events/yr have been observed with flux $\Phi_\gamma(>45$ TeV$)>3.2\cdot10^{-11}$ cm^{-2} s^{-1} and duration Δt$<$ 7.5 hrs (calculated for a zenith-culminating source).

A coincident excess in the number of counts from Mrk421 observed on 15th January, 1994, has a chance imitation rate n$_{ch}$ =0.01. The operation of the arrays has been proved to be at statistical level, thus demonstrating the reliability of the reported confidence level. This candidate episode would prove that the gamma-ray spectrum of AGNs, during flaring activity, extends up to primary energies $\approx 5\cdot 10^{13}$ eV (with $\Phi_\gamma = (1\div2)\cdot10^{-11}$ cm^{-2} s^{-1}), with no significant absorption on infrared photons in the intergalactic space at such energies up to the distance of Mrk 421 (z=0.031).

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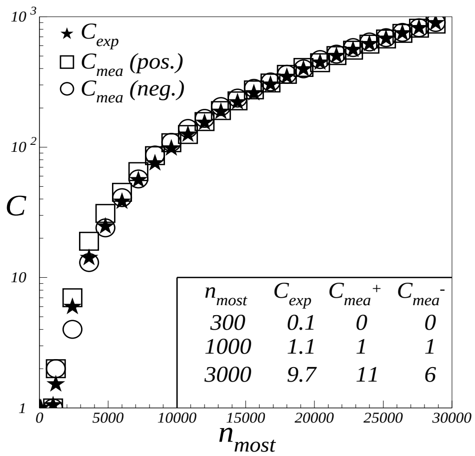

Figure 3: *Comparison of observed and expected number of coincident largest positive and negative excesses.*

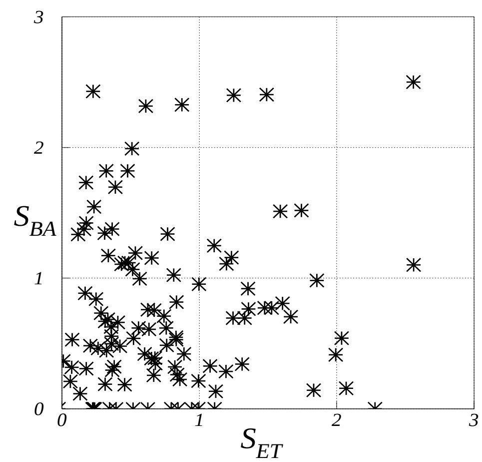

Figure 4: *Plot of positive excesses in EAS-TOP (S_{ET}) and Baksan (S_{BA}) in 349 days of observation of Mrk 421.*

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