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Search for PeV γ-ray sources with the GAMMA experiment

Y.A. Gallant[a], A.P. Garyaka[b], L.W. Jones[c], R.M. Martirosov[b], N.M. Nikolskaya[d], J. Procureur[e], and S.V. Ter-antonyan[b]

(a) Laboratoire de Physique Théorique et Astroparticules, Université Montpellier II, 34095 Montpellier Cedex 5, France
(b) Yerevan Physics Institute, Br. Alikhanyan Str. 2, 375036 Yerevan, Armenia
(c) Department of Physics, University of Michigan, Ann Arbor, MI 48109-1120, U.S.A.
(d) Moscow Lebedev Institute, Leninsky Pr. 56, Moscow, Russia
(e) Centre d'Etudes Nucléaires de Bordeaux-Gradignan, "Le Haut Vigneau", 33175 Gradignan Cedex, France
Presenter: R. Martirosov (martir@mail.yerphi.am), arm-martirosov-R-abs3-og22-poster

We examine the prospects for γ-ray astronomy in the PeV energy domain using the extensive air shower (EAS) detector array GAMMA, situated at 3200 m a.s.l. on Mt. Aragats, Armenia. The gamma-ray fluxes which could be expected from the sources of Galactic cosmic rays, based on extrapolation of recent observations in the TeV energy domain, are presented. We then discuss their detectability in the context of a search for point-like sources in the EAS data of the GAMMA experiment, taking into account sky observability from Mt. Aragats and the uncertainties in shower direction reconstruction. Preliminary results of a search for such point-like sources are presented. The prospects for improved sensitivity to γ-ray showers with selection criteria based on the GAMMA muon data, as well as with planned improvements in the trigger condition, are discussed.

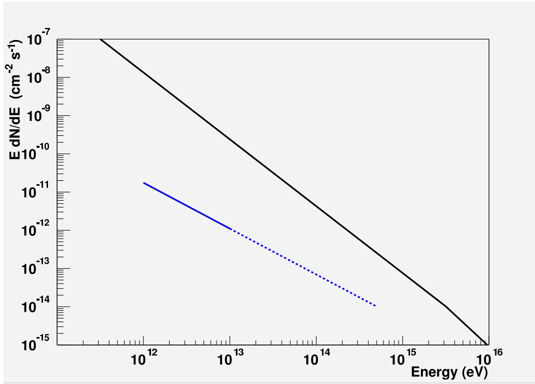
1. Introduction and astrophysical motivation

The GAMMA experiment is an extensive air shower detector array situated at an altitude of 3200 m a.s.l. on Mt. Aragats in Armenia; a detailed description of the development and current status of this experiment is given in [6]. It consists of two principal parts: an array of surface scintillation detectors to measure the electromagnetic component of the EAS, and an underground muon detector "carpet". The accumulated EAS data have been used extensively to study the spectrum and composition of the primary cosmic rays in the energy range $10^{15} - 10^{17}$ eV (see e.g. [8]). In what follows, we focus on issues and prospects specific to the detection of astrophysical sources of γ-rays using the GAMMA air shower data.

Almost a century after the discovery of cosmic rays, which must be of Galactic origin at least up to the energy of the "knee" at a few times 10^{15} eV, the nature of their sources remains uncertain. The charged Galactic cosmic rays (GCRs) themselves can provide only very indirect clues to their origin, due to their confinement and diffusion in the Galactic magnetic field. On the other hand, γ-rays travel undeflected by this magnetic field, and can be produced by hadronic processes in the sources of the GCRs if a sufficiently dense target medium is present. γ-rays may thus hold the key to the identification of the GCR sources.

The most frequently proposed scenario for the origin of GCRs is acceleration at the blast wave of supernova remnants (SNRs). The H.E.S.S. experiment has recently unambiguously confirmed the detection of γ-rays in the TeV energy domain from the shells of the SNRs G 347.3–0.5 [1] and G 266.2–1.2 [3]. These sources are significantly extended, with diameters of about 1° and 2°, respectively, and exhibit relatively hard power-law spectra, $\mathrm{d}N/\mathrm{d}E \propto E^{-\Gamma}$, with spectral indices Γ around 2.2 and 2.1. Most of the new sources discovered in the H.E.S.S. Galactic plane survey are also extended, and several seem to be associated with SNRs [2].

The observed hard spectra are consistent with theoretical expectations for particle acceleration in SNRs, and also with the predicted source spectrum of cosmic rays, taking into account their energy-dependent propagation in the Galaxy (e.g. [5]). If the observed TeV γ-rays are the long-sought hadronic signatures of the GCR sources, and if cosmic rays are accelerated up to the "knee" energy in these objects, then the γ-ray spectra should extend



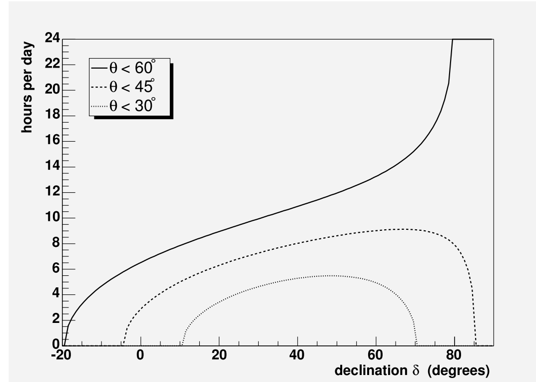


Figure 1. a (left) Schematic representation of the total cosmic ray spectrum (black line), integrated over a region 1° across, and of the observed TeV spectrum of G 347.3–0.5 and its extrapolation to the "knee" energy (blue line). **b** (right) Visibility of the celestial sky from the location of GAMMA on Mt. Aragats, in hours per day at less than a given zenith angle, as a function of sky declination.

smoothly up to the PeV energy region (see Fig. 1a). The ratio of the γ-ray to charged cosmic-ray fluxes would then increase with energy, due to the latter's steeper spectral index of about $\Gamma = 2.65$, making the detection of the γ-ray sources correspondingly easier at PeV energies.

G 347.3–0.5 and G 266.2–1.2 are in the Southern hemisphere, and thus not observable by GAMMA given their declinations, $\delta \sim -40°$ and $-46°$ respectively (see Fig. 1b). However, extended sources of TeV γ-rays with comparable fluxes have recently been detected by the Milagro experiment [7], and may consist of similar objects. The Northern declinations of these latter sources makes them optimally observable by GAMMA.

2. Relevant parameters of the GAMMA experiment

A critical parameter in a search for localised astrophysical sources is the accuracy with which the arrival direction of each primary particle can be determined. In the GAMMA data analysis, the shower zenith and azimuth angles θ and ϕ are determined using the timing information from the surface scintillation detectors to reconstruct the orientation of the EAS front. The accuracy of this angular reconstruction can be estimated from the experimental data themselves by comparing the directions obtained using timing information from two independent subsets of surface detectors.

Figure 2a shows the results of such a comparison between the shower angles (θ_1, ϕ_1) and (θ_2, ϕ_2) obtained using the odd- and even-numbered surface detectors, respectively. For this analysis, we selected only showers with age parameter $0.3 < s < 1.6$, zenith angle $\theta < 45°$, and number of charged particles $N_e > 3 \times 10^5$, in order to optimise the angular resolution. The measured values of $\langle(\theta_2 - \theta_1)^2\rangle$ and $\langle\sin^2\theta(\phi_2 - \phi_1)^2\rangle$ can then be used to estimate the uncertainties in the angles reconstructed using all detectors [4]; this yields $\sigma_\theta \approx 1.6°$ and $(\sin\theta)\sigma_\phi \approx 1.6°$ for the EAS selection criteria described above.

Equally important is an accurate transformation between these angular coordinates and sky coordinates. This depends on a precise knowledge of the installation's geographical location and orientation, as well as the time of each event. A portable GPS device was used in December 2004 to measure more accurately these

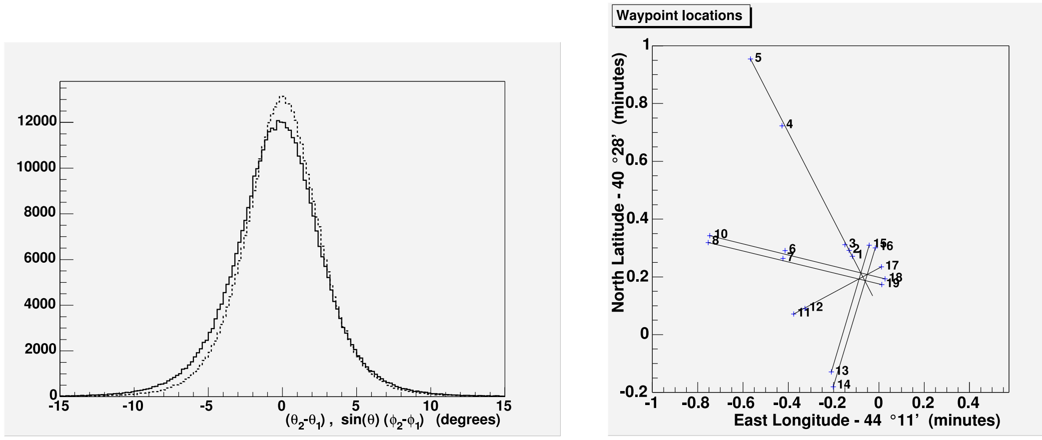


Figure 2. **a** (left) Distribution of the angular differences $\theta_2 - \theta_1$ (solid line) and $\sin\theta(\phi_2 - \phi_1)$ (dashed line) determined using two independent subsets of surface detectors (see text). **b** (right) Measured GPS waypoints used to determine the geographical coordinates and orientation of the GAMMA array.

geographical parameters. The latitude and longitude of the center of the GAMMA array were determined to be $40°28'12''$ North and $44°10'56''$ East, respectively.

The orientation of the GAMMA array was also determined with the GPS using long baselines parallel to the array axes (see Fig. 2b), yielding an orientation angle ϕ_0 relative to geographical North of $16° \pm 1°$. The value of this orientation angle was confirmed in 2005 with solar shadow angle measurements, which yielded values around $15°$. Nonetheless, the remaining uncertainty in ϕ_0, currently of order $1°$, contributes a corresponding systematic error in the determination of the EAS azimuth angles relative to geographical North.

3. Preliminary results

Using the above-determined values, the arrival directions of recorded EAS satisfying the above selection criteria were converted to right ascension and declination, to perform a preliminary search for enhancements in the high-energy particle flux from any direction in the observable sky. The two-dimensional sky coordinate histogram of recorded showers was binned to match the angular resolution of the direction reconstruction.

To search for localised sources, the number of events in each sky bin was compared with the number expected from a smooth background model. This model consisted of a sinusoidal variation in right ascension, fitted to the overall distribution, and then appropriately normalised in each declination band. The significance of the deviation in each bin was computed, and the resulting sky map is shown in Fig. 3a. The distribution in significance of the observed deviations, shown in Fig. 3b, is compatible with random fluctuations, and thus we find no significant evidence for point sources at any position in the sky map.

4. Discussion

Recently improved determinations of the uncertainties in EAS direction reconstruction and of the geographical parameters of the GAMMA experiment have allowed us to compute more reliable sky maps of the primary

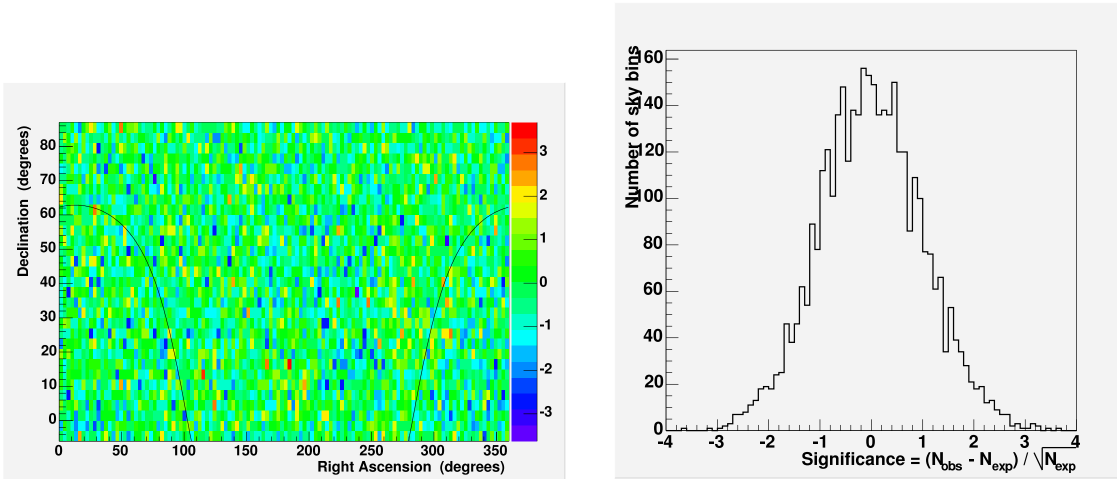


Figure 3. **a** (left) Sky significance map of selected EAS recorded by the GAMMA experiment (see text); the solid line indicates the Galactic plane. **b** (right) Significance distribution of the observed deviations from the background.

particle arrival directions. In such an analysis of the available GAMMA EAS data, we find no evidence for localised astronomical sources of high-energy particles.

Using information from the muon detectors to select muon-poor showers should in the near future allow us to perform similar searches with increased sensitivity; optimised shower selection criteria for this purpose are currently under investigation. A planned modification of the trigger condition, also under study, should allow the acquisition of relevant events at an increased rate, thereby improving the accumulation of statistics in the GAMMA data bank. These data could help constrain spectral models for hard-spectrum γ-ray sources detected at TeV energies, in particular for extended sources.

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