Search for Sources of Cosmic Rays in the Region of the Knee. II

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Abstract

New results of an analysis of arrival directions of extensive air showers registered with the EAS–1000 Prototype array from August 1997 till February 1999 are presented. The method of Alexandreas et al., which has been used for analysis of data registered with CYGNUS, Milagrito, HEGRA AIROBICC, KASCADE and a number of other experiments, is employed. The existence of zones of excessive flux of cosmic rays with energies in the region of the knee is confirmed, as well as closeness of the zones to coordinates of possible astrophysical cosmic ray sources.

1. Introduction

We have already studied arrival directions of extensive air showers (EAS) with energies of primary particles of the order of $10^{14}$–$10^{15}$ eV registered with the EAS–1000 Prototype array [1, 2]. In these works, the analysis was performed with the help of a special procedure of filtering experimental data which allowed us to obtain a set of data such that at some scale, the showers were distributed uniformly wrt. sidereal time and the azimuth angle. In this method, filtering of data was done in a (pseudo-)random way. Thus, in what follows, we shall call this procedure as a method of random filtering (MRF). A detailed description of the MRF can be found in [1, 2].

The MRF applied to our data set resulted in the selection of 37 zones of excessive flux (ZEFs) of EAS. Location of the majority of the ZEFs was found to be close to the coordinates of possible astrophysical sources of cosmic rays (CRs) with energies in the region of the knee in the energy spectrum at around 3 PeV [3]. The fact that application of the MRF to the available data set led to exclusion of about 17% of the initial number of EAS with known arrival directions, motivated us to perform a similar analysis basing on the method of Alexandreas et al. [4]. This method utilizes the full amount of available data. It has been successfully employed earlier in a number of investigations, see, e.g., reports on the analysis of data obtained with the CYGNUS [4], Milagrito [5], Milagro [6], HEGRA AIROBICC [7], and KASCADE [8] experiments. Below we present the results of our investigation.

2. Experimental Data

The data set under consideration includes 1,668,489 EAS registered during 203 days of operation of the EAS–1000 Prototype Array in the period from August 30, 1997, till February 1, 1999. The array consisted of eight detectors located in the central part of the EAS MSU array along longer sides of the 64 m × 22 m rectangle [9]. The geographical coordinates of the array were 37°32.5′E, 55°41.9′N.

Arrival directions were determined for 1,366,010 EAS. A number $N_e$ of charged particles (electrons) was found for 826,921 EAS. The mean value $\bar{N}_e = 1.20 \times 10^5$ corresponds to the energy of a primary proton $E \approx 10^{15}$ eV. There are only 11262 EAS with $N_e > 10^6$ but they give a noticeable contribution in the value of $\bar{N}_e$. With the above energetic EAS excluded, $\bar{N}_e = 7.65 \times 10^4$ and the median value equals $3.62 \times 10^4$. Thus, the majority of showers in the data set under consideration had primary particles with energies slightly below the knee.

3. Method of Investigation

The main idea of the method of Alexandreas et al. [4] is the following. A search for ZEFs is based on the comparison of real experimental data set with a “background” set that would be registered with the same installation and during the same period of observation in the assumption of a uniform distribution of arrival directions of EAS over the celestial sphere. The background data set is obtained by a simple procedure of
randomization. First, for every shower with an arrival direction \((\theta, \varphi)\) an arrival time \(t'\) of another shower is chosen randomly from the rest of the experimental data set. Next, arrival directions of all showers in the equatorial coordinates \((\alpha, \delta)\) are calculated basing on the respective triplets \((t', \theta, \varphi)\). In the resulting set, the distribution of EAS wrt. \(\delta\) is exactly the same as in the original data set.

Randomization is performed multiple times in order to avoid a dependency of the distribution wrt. \(\alpha\) on the concrete choice of \(t'\). After this, one creates an averaged “background” map by calculating the mean number of EAS located in cells of a fixed size \(\Delta \alpha \times \Delta \delta\) in all obtained maps. It is believed that the background map has most of the properties of an isotropic background [8]. A search for ZEFs is performed by comparing the number of EAS in a region in the original (“real”) experimental map with the same region in the background map. The measure of deviation is the significance \(S = (N_{\text{real}} - N_{\text{bg}})/\sqrt{N_{\text{bg}}}, \) where \(N_{\text{real}}\) and \(N_{\text{bg}}\) are the numbers of EAS in the same region of the “real” experimental map and the background maps respectively.

For the purposes of this investigation, the background map was obtained by averaging the number of showers binned in \(\Delta \alpha \times \Delta \delta = 1^\circ \times 1^\circ\) cells. An analysis of the background maps revealed that two maps obtained consecutively differ by at most 1% of the number of EAS in the respective cells after around 50 cycles of randomization, and by 0.5% after 90 cycles. Thus we chose to perform 100 cycles of randomization to obtain the final background map.

To look for ZEFs, we followed the same procedure as we used in [1, 2]. Namely, the field of observation was divided into strips of width \(\Delta \delta = 3^\circ \ldots 30^\circ\), with the boundaries of the strips of equal width shifted by \(1^\circ\) wrt. each other. Each strip was then divided into cells of equal width \(\Delta \alpha\). In the main part of the investigation, for any fixed width \(\Delta \delta\) of a strip, \(\Delta \alpha\) was chosen to be equal to a rounded value (expressed in degrees) of \(\Delta \delta / \cos \delta\), where \(\delta\) is the mean value of the declination for the strip. This guarantees that cells with the same \(\Delta \delta\) but located at different declination, have an approximately equal area. Similar to [1, 2], such cells will be called ‘regular’. It is important to take into account that neither the method of Alexandreas et al., nor the method of random filtering put a restriction on the way one chooses regions to be compared. One may perform a search for ZEFs with an arbitrary relation of \(\Delta \alpha\) and \(\Delta \delta\), as well as ZEFs of an arbitrary shape.

4. Main Results

Application of the method of Alexandreas et al. to the available data set resulted in the discovery of 561 regular cells with \(S > 3.0\). For 364 of these cells, significance \(S > 3.1\). For the sake of convenience, the cells were joined into 27 zones such that each zone is a connected domain. In order to perform an accurate comparison of the results of the two methods, we added five zones made of “irregular” cells, i.e., cells with an arbitrary relation of \(\Delta \alpha\) and \(\Delta \delta\). The resulting ZEFs are shown in Fig. 1 in red. The most of partially overlapping cells of excessive flux are not shown for the sake of visual clarity. Their joint exterior boundaries are shown instead. Blue lines show the boundaries of the ZEFs presented in [1, 2]. Recall that all of these 37 ZEFs but zones No. 4, 5, 6, 20, and 21, and bigger cells in ZEFs No. 3, 27, 29, 33, and 36 are composed of regular cells. A number of the zones found by the MRF coincide with those found by the method of Alexandreas et al. and thus their boundaries are not visible in the figure.

As is clear from Fig. 1, the results obtained by two different methods are quite close, though the MRF seems to be more selective in the sense that the total area of ZEFs found by this method is less than that of the zones found by the method of Alexandreas et al. (“A-zones”). In sum, 20 ZEFs found by the MRF lie inside A-zones. These are zones No. 1–9, 12, 14, 15, 18, 22, 25–28, 31, and 36. Zone No. 30 also lies inside the corresponding A-zone excluding a small area \(\Delta \alpha \times \Delta \delta = 3^\circ \times 1^\circ\). A major part of ZEF No. 32 also lies within the corresponding A-zone. Zones No. 11, 17, and 21 exactly coincide with A-zones, while zones No. 13 and 33–35 coincide with A-zones up to \(1^\circ\). In fact, there are multiple coincidences with deviation of at most \(1^\circ\) of separate cells found my the two methods in all cases when a “composite” ZEF found by the MRF is embedded into a zone found by the method of Alexandreas et al.

Let us mention the existence of pairs for the central cell in ZEF No. 16, which has the M33 galaxy located inside, and for ZEF No. 7, which contains the famous C2 triplet of ultra-high energy cosmic rays, registered with the AGASA array [10]. Recall that the observation of the latter coincidence was one of the motivations for the analysis of coordinates of extra-galactic cosmic ray sources performed in [2].

An embedding of A-zones into the ZEFs found by the MRF can be seen in a few cases. Namely, ZEF
Figure 1: Red lines show the boundaries of ZEFs found by the method of Alexandreas et al. Blue lines show the boundaries of ZEFs found by the method of random filtering. Numbers in the field of the figure show the numbers of ZEFs assigned to them in [1, 2]. The (magenta) arcs show the Galactic plane. The ∩-like curve shows the Supergalactic plane.

No. 10, 23, 24, and 29 contain the corresponding A-zones inside. Only three of 37 ZEFs found by the MRF do not have close counterparts among A-zones. These are the irregular ZEF No. 20, the irregular (exterior) cell of ZEF No. 29, and ZEF No. 37. In the latter case, there are a number of irregular A-zones that intersect the ZEF. They are shown in the figure.

Finally, notice seven A-zones (made of regular cells) that do not have any close counterparts among the ZEFs found by the MRF. These are a zone located around α = 20°, δ = 75°, two big A-zones in the vicinity of δ = 70°, a zone near α = 330°, δ = 73°, a zone around α = 290°, δ = 60°, and two zones near δ = 10° (α = 25...29° and α = 224...229° respectively).

5. Discussion
In our opinion, there is a qualitative agreement between the results of the analyses of arrival directions of cosmic rays registered with the EAS–1000 Prototype Array performed by two different methods. The agreement confirms one of the main conclusions of [1, 2] that there are zones of excessive flux of EAS in the available data set. We find it remarkable that mutual coincidences or embeddings are observed for all zones located in the vicinity of the Galactic and Supergalactic planes.

Let us now consider correlations between positions of the ZEFs and coordinates of possible astrophysical sources of cosmic rays with energies near the knee. Figure 2 shows A-zones that have close counterparts among the ZEFs presented in [1, 2] and coordinates of galactic supernova remnants (SNRs) [11], pulsars [12] (as of the state on June 19, 2006), and active galactic nuclei (AGN) and interacting galaxies at red shifts z ≤ 0.01 [13]. All shown astrophysical objects have coordinates at angular distances ≤ 3° from the closest A-zone. This criterion selected 18 of 110 SNRs at δ > −16° with 15 of them lying inside A-zones and two of them lying at angular distances ≤ 1.5°, 154 of 694 pulsars, and 139 of 317 AGN and interacting galaxies. In particular, the selected objects include the famous SNRs SN1181, 3C461 (Cas A), SN1572 (Tycho), and the Crab Nebula, a number of pulsars located at distances < 0.5 kpc from the Solar system, as well as the active galactic nuclei NGC 3718, NGC 2681, NGC 4278, Mrk 1307, M105, M64, M65, M66, etc., which have red shifts z ≤ 0.0033. Notice that the Virgo cluster of galaxies lies inside a huge A-zone located along the Supergalactic plane (α ≈ 170°...200°). It is evident that there are numerous coincidences between coordinates of possible astrophysical sources of cosmic rays with energies near the knee and positions of zones located in the vicinity of the Galactic and Supergalactic planes.
Figure 2: Zones of excessive flux found by the method of Alexandreas et al. [4] that have counterparts among the ZEFs found in [1, 2]. Different symbols show coordinates of some astrophysical objects that have coordinates within angular distance ≤ 3° from the ZEFs. These are galactic supernova remnants (●), pulsars (filled blue triangles), active galactic nuclei and interacting galaxies at red shifts z ≤ 0.01 (∆). Also shown are the coordinates of the C2 triplet registered with the AGASA array (*) [10] and the M33 galaxy (the red box).

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