Few-degree anisotropies in the cosmic-ray flux observed by the ARGO-YBJ experiment

G. DI SCIASCIO[1] AND R. IUPPA[1,2]
ON BEHALF OF THE ARGO-YBJ COLLABORATION
[1] *INFN, Sezione di Roma Tor Vergata*
[2] *Department of Physics, University of Tor Vergata*
roberto.iuppa@roma2.infn.it

Abstract: The ARGO-YBJ experiment is a full coverage EAS array sensitive to gamma rays and cosmic rays with energy threshold few hundreds GeV. We analyzed the data taken since November 2007 looking for few-degree anisotropies in the arrival directions of cosmic rays. We found several regions with significant excesses (up to 17 s.d.), whose relative intensity with respect to the isotropic flux extends up to 10^{-3}. The maximum excess occurs for proton energies of 10 TeV, suggesting the presence of unknown features of the magnetic fields the charged cosmic rays propagate through, as well as potential contributions of nearby sources to the total flux of cosmic rays.

Keywords: Extensive Air Showers, Cosmic Rays, Anisotropy, ARGO-YBJ

Introduction

So far, no theory of cosmic rays in the Galaxy exists which is able to explain few degrees anisotropies of charged cosmic rays in the rigidity region 1-10 TV. Apart from Compton-Getting effects, which are due to the relative motion of the obeserver and the fluid around him, no absolute excesses or lacks are foreseen below 10^{15}eV. More beamed the anisotropies and lower their energy, more difficult to fit the standard model of cosmic rays and galactic magnetic field to experimental results.

In 2007, modeling the large scale anisotropy of 5 TeV cosmic rays, the Tibet-ASγ collaboration ran into a “skewed” feature in the “tail in” region [1, 2]. They modelized it with a couple of intensity excesses in the hydrogen deflection plane, each of them $10^\circ - 30^\circ$ wide. Afterwards the Milagro collaboration claimed the discovery of two localized regions of excess 10-Tev cosmic rays [3]. Regions “A” and “B”, as they were named, are positionally consistent with the “skewed feature” observed by Tibet-ASγ and were parametrized as:

$$\begin{array}{rrr} \text{region“A”}: & 117^\circ \leq \text{r.a.} \leq 131^\circ & 15^\circ \leq \text{dec.} \leq 40^\circ \\ & 131^\circ \leq \text{r.a.} \leq 141^\circ & 40^\circ \leq \text{dec.} \leq 50^\circ \\ \text{region“B”}: & 66^\circ \leq \text{r.a.} \leq 76^\circ & 10^\circ \leq \text{dec.} \leq 20^\circ. \end{array}$$

Both detectors and methods of data-analysis were quite different and only the Milagro collaboration excluded the hypothesis of gamma-ray induced excesses. Recently the IceCube collaboration published the most extensive search of cosmic-ray anisotropies in the southern emisphere ever[4]. They found features fully compatible with the observations of the aforementioned Northern emisphere experiments. It is worth noting that the IceCube experiment measures muons, making us confident that charged cosmic rays of energy above 10 TeV are observed.

All the same, galactic (i.e. $\leq 10^{15}$ eV) charged cosmic-ray arrival directions are thought to be isotropic, owing to the action of the magnetic fields they propagate through before reaching the Earth atmosphere. The galactic magnetic field is the superposition of regular field lines and chaotic contributions. Altough the strength of the non-regular component is still under debate, the local total intensity is supposed to be $B = 2 \div 4\ \mu$G [5]. In such a field, the gyroradius of cosmic rays is given by:

$$r_{a.u.} = 100\, R_{\text{TV}}$$

where $r_{a.u.}$ is in astronomic units and R_{TV} is in TeraVolt.

As will be delt in later on, the excesses are $10^\circ - 30^\circ$ wide and no interpretation holds leaving the standard model of cosmic rays and that of the local galactic magnetic field unchanged at the same time.

First interpretations based on observing the excess are inside the “tail-in” zone of the large scale anisotropy, which is named after the heliotail. That induced authors to suggest their experimental results are due to interactions of cosmic rays with the heliosphere[3]. Several authors, noticing that the effects of the heliosphere on cosmic rays are usually in the GeV region, proposed a model where the excesses are produced in the Geminga supernova explosion [6]. In the first variant of the model cosmic rays simply diffuse (Bohm regime) up to the solar system, while the second limits the diffusion to the very first phase of the process and appeals to non-standard diverging magnetic field structure to bring them here. Other people [7] proposed similar schemes involving local sources and magnetic traps guiding cosmic rays to the Earth. It must be noticed that sources are always intended to be near-by, at less than 100-150 pc. Moreover the positions of the excesses in galactic coordinates, symmetrical with respect to the galactic plane and at the anti-center longitude, has been important in inspiring such models.

More recently, some ideas that do not involve nearby sources have been proposed. The hypothesis that the effect could be related to the interaction of isotropic cosmic rays with the heliosphere has been re-proposed by [8]. Grounding on the coincidence of the most significant localized regions with the heliospheric tail, magnetic reconnection in the magnetotail has been shown to account for beaming particles up to TeV energies. There has been also the suggestion that cosmic rays might be scattered by strongly anisotropic Alfven waves originating from turbulences across the local field direction[9].

Besides all these "ad hoc" interpretations, several attempts occurred in trying to insert the cosmic-ray excesses in the framework of recent discoveries from satellite-borne experiments, mostly as far as leptons are concerned. In principle there is no objection in stating that few-degree cosmic-ray anisotropies are related to the positron excess observed by Pamela [10] and to the electrons excess observed by Fermi [11]. All observations can be looked at as different signatures of common underlying physical phenomena.

ARGO-YBJ reports here the observation of the region "A" and "B" with unprecedented detail, giving important informations on their shape and their extension. Moreover several sub-structures have been found and new weaker few-degree excesses throughout the sky region $195^\circ \leq r.a. \leq 315^\circ$.

1 The ARGO-YBJ experiment

The ARGO-YBJ experiment [13] is a wide field of view air shower array located at the YangBaJing Cosmic Ray Laboratory (Tibet, P.R. China, 4300 m a.s.l., 606 g/cm^2). It exploits the full coverage with a central carpet $\sim 74 \times 78 \mathrm{m}^2$ made of a single layer of Resistive Plate Chambers with $\sim 93\%$ active area, enclosed by a guard ring partially instrumented to improve the angular resolution. It is operated with a duty-cycle higher than 85% since November 2007 with trigger rate intrinsically stable at level 0.5%. The high altitude, as well as the full coverage approach, reduce the energy threshold of this EAS array down to few hundreds GeV. The event reconstruction [14, 15] guarantees angular resolution well below the angular scales dealt with in this paper.

2 Data analysis

The data used for the present analysis have been taken from November 2007 to November 2010. All events firing 40 strips or more in the central carpet have been used. Among them, only those with reconstructed zenith angle less than or equal to 50° were used to fill the maps. The triggering showers that passed the selection above were $1.27\,10^{11}$. The zenith cut selects the declination region $\delta \sim -20^\circ \div 80^\circ$.

The isotropic background of cosmic rays has been estimated with methods based on time-average. They rely on the assumption that the local distribution of the incoming cosmic rays is slowly varying and the time-averaged signal may be used as a good estimation of the background content. We applied both Direct Integration and Time Swapping methods ([12]), finding no differences in the background maps within 1 s.d. Since techniques are equivalent, we present here results obtained with the Direct Integration method. All the events selected have been used to compute the background map, because signal regions are so extended to make impossible excluding them (as we normally do for point-like sources). It follows that the background level is slightly overestimated. Two consequences of such a "source inclusion" are important: first, the significance of the excesses is underestimated ($\sim 3.5\%$ if the significance is 15 s.d.); second, fake significant deficit regions arise around the excess ones. Since the localized excesses are less than 10^{-3}, the systematic error induced on the estimation of the intensity is negligible; on the significance front, the values we obtained are that high (up to 17 s.d. pre-trials, depending on the opening angle) to make us confident about our result even when this bias is accounted for with the most pessimistic assumptions.

Time-averaging methods act effetively as a high-pass filter, not allowing to inspect features larger than the time over which the background is computed. The time interval used to compute the average spans 3 hours and makes us confident the results are reliable for structures up to 45° wide.

Actually, since one of the most significant feature at few degrees scale is found to be coincindent with the large scale structure named "heliotail", in order to establish whether any relation is present between the two signals, background estimation techniques common to all angular scales should be used.

3 Results

Figure 1 shows the ARGO-YBJ sky map as obtained from all events analyzed as mentioned in the previous paragraph. Data are looked at with opening angle 5° wide. This choice is the best compromise for having a good high-frequency noise reduction and sufficient details to determine the actual regions size. The upper plot shows the significance of the observation according to the Li&Ma statistics while the lower the intensity relative to the estimated background.

They look slightly different because of the efficiency of the ARGO-YBJ experiment, which is dominated by the atmosphere thickness the showers must cross before triggering the apparatus. As a consequence most significant regions do not necessarily coincide with most intense excesses. The most evident features rest in the right side of the map and coincide spatially with regions “A” and “B” detected by Milagro [3]. However, the choice of using an opening angle 5° wide[1] allows to distinguish several substructures: in particular, region “B” appears to be made of two distinct hot-spots and those of region “A” do not seem so different in size. Unfortunately, region “A” partially falls off the ARGO-YBJ field of view and no complete information about its shape can be obtained.

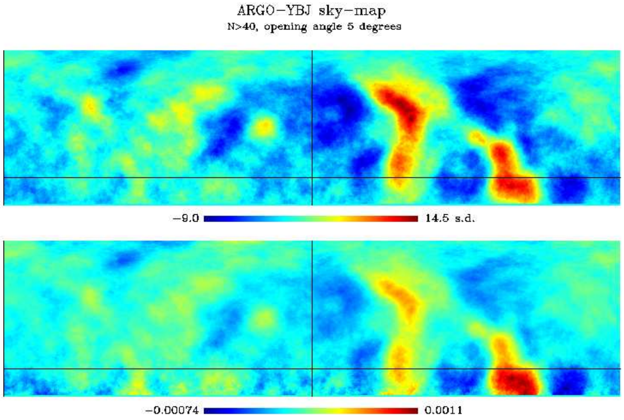

Figure 1: ARGO-YBJ sky-map in celestial coordinates. Opening angle 5°. *Upper plot:* significance of the observation. *Lower plot:* relative excess with respect to the estimated background.

On the left side of the maps, several new extended features are well visible, though less intense than those aforementioned. Apart from the Cygnus region (far left of the map), which is known to host several vivid TeV gamma-ray sources, the area $195^\circ \leq r.a. \leq 315^\circ$ seems to be full of few-degree excesses not compatible with random fluctuations. The observation of these structures is reported here for the first time and together with that of regions “A” and “B” it may open the way to an interesting study of the TeV cosmic-ray sky.

3.1 The energy spectrum

To figure out the energy spectrum of the excesses, data have been divided into five independent multiplicity sets, according to the number of strips they fired on the central carpet. The multiplicity intervals are: 40-99, 100-249, 250-629, 630-1600 and > 1600.

Figure 2 shows the evolution of the anisotropies with the multiplicity of the detected showers. The upper map shows the map of the relative intensity for $40 \leq N_{strip} < 99$, the intermediate for $100 \leq N_{strip} < 249$ and the lower for $250 \leq N_{strip} < 629$. The opening angle is still 5°. What is worth noting is that the excess intensity increases with the energy and for all regions under consideration. Moreover, the highest energy (i.e. the highest rigidity) map suggests the excesses lay on angular scale of $5^\circ - 10^\circ$ and what appears to be merged at lower energies seems to be well separated a factor 10 above (see region “A” for instance).

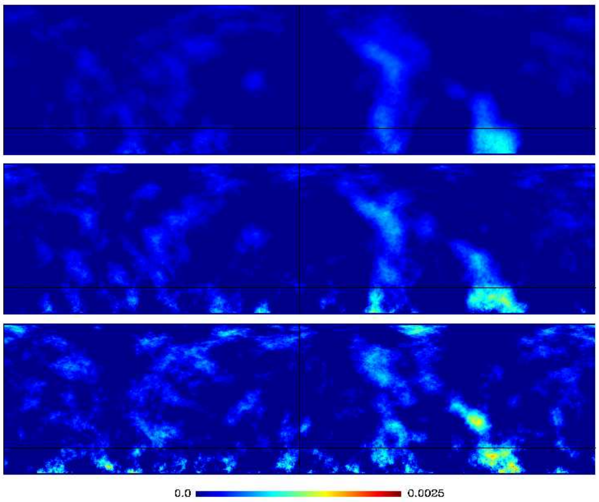

Figure 2: Evolution of the cosmic ray intermediate scale features with the energy. The color scale spans 0 to 10^{-3}. See the text for details.

As a preliminary result, we computed the energy spectrum of the two most intense excesses, for which we used the parametrization introduced by the Milagro collaboration[3]. It must be noticed that this choice is not the optimal one for ARGO-YBJ, because altough positionally consistent, regions “A” and “B” appear to have shapes quite different from those observed by Milagro.

The number of events collected within each region are computed for the event map as well as for the background one. The ratio of these quantities is computed for each multiplicity interval. The result is shown in figure 3, where the lower panel stands for reference of the multiplicity-energy relation in case of protons. Region “A” seems to have spectrum harder than isotropic cosmic rays and a cutoff around 600 fired strips (proton median energy $E_p^{50} = 8$ TeV). On the other hand, the excess hosted in region “B” is less intense and has a spectrum well distinguished from that of isotropic cosmic rays, harder from 100 fired strips on ($E_p^{50} = 2$ TeV). Moreover, there is a hint of flattening at lower multiplicites.

It must be said that these results are strictly related to the definition of the excess regions. For comparison, we choose the only existing parametrization at this time, but the spectrum estimation in sensitive to the shaping of re-

---

[1] This value is half that used by [3].

gion “A” and “B”. These aspects of the analysis are still under investigation.

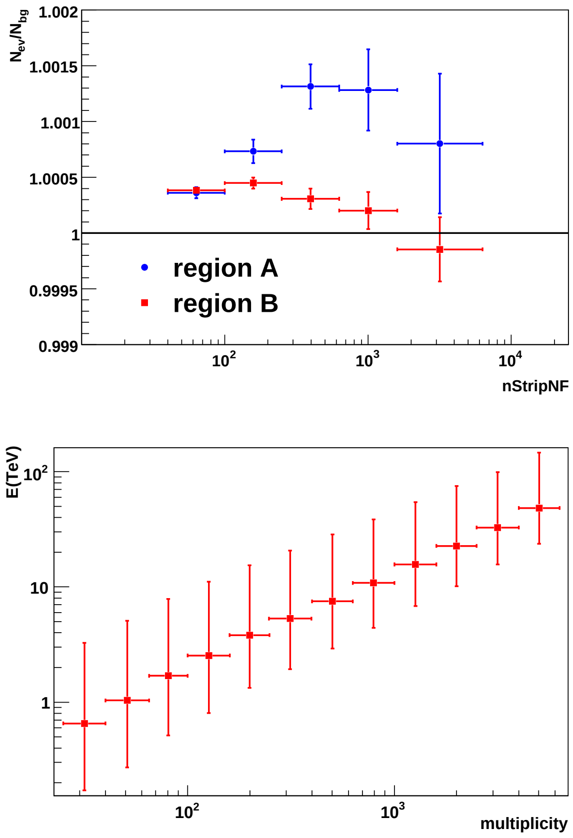

Figure 3: Energy spectrum of the region “A” and “B” excesses. The horizontal axis represents the number of fired strips. The vertical axis represents: the ratio between the events collected *(upper panel)*; the median energy for proton-induced showers *(upper panel)*.

3.2 Galactic view

As we mentioned in the Introduction, theoretical interpretations were much inspired by the position of the hot spots “A” and “B” in Galactic coordinates. As it is clearly visible in figure 4, they are distributed symmetrically with respect to the Galactic plane and have longitude directed towards the galactic anti-center. As for the new detected hot spots, they do not stay along the galactic plane, even one of them is very close to the galactic north pole. More details will be given by the ARGO-YBJ collaboration in the next future.

4 Conclusions

Thanks to the operational stability, the high duty-cycle, as well as the very good angular resolution, the ARGO-YBJ experiment detected several few-degree cosmic-ray excesses in three years of data acquisition. The observation has high statistical significance and confirms findings by other experiments like Tibet-ASγ and Milagro. Nonetheless the morphological description of the phenomenon has been greatly improved by ARGO-YBJ and new localized sky portions hosting excesses have been found. Energy spectra have been measured for region “A” and “B”. They have been found to be rather similar to mesurements by previous experiments, though significant differences can be appreciated, mostly for what concerns region “B”. The physical world resulting from these observations is not explainable in terms of the standard model of cosmic rays propagation in the galaxy. If the explanation is really related to the emission from a nearby sources, few-degree anisotropies may reveal as an effective tool to probe the accelerated emission of cosmic rays at sources.

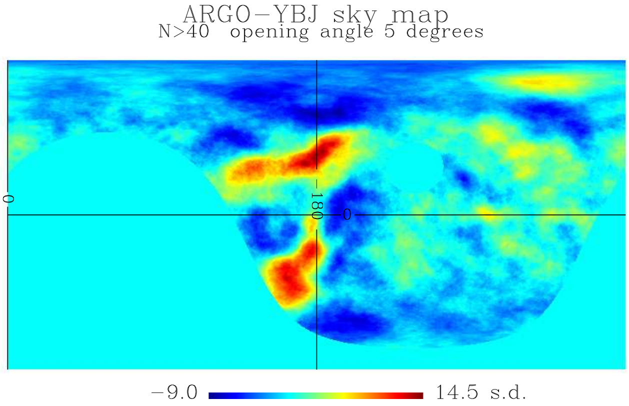

Figure 4: ARGO-YBJ sky-map in galactic coordinates. Opening angle 5°. The map center points towards the anti-center.

References

[1] M. Amenomori *et al.* , AIP Conf. Proc., 2007, **932**: page 283-289
[2] M. Amenomori *et al.* , 31^{st} ICRC conf. proc., 2009
[3] A. A. Abdo *et al.* , Phys. Rev. Lett., 2008, **101**(221101)
[4] R. Abbasi *et al.* , ApJ, in press, preprint: arXiv:1105.2326
[5] R. Beck, Space Sci. Rev., 2001, **99**(1/4): page 243-260
[6] M. Salvati *et al.* , A&A, 2008, **485**(2): page 527-529
[7] L. Drury *et al.* , Astropart. Phys., 2008, **29**(6): page 420-423
[8] A. Lazarian, P. Desiati, ApJ, 2010, **722**: page 188-196
[9] M. A. Malkov *et al.* , ApJ, 2010, **721**: page 750-761
[10] A. Adriani *et al.* , Nature, 2009, **458**: page 607
[11] A. A. Abdo *et al.* , PRL, 2009, **102**(181101)
[12] R. Fleysher *et al.* , ApJ, 2004, **603**: page 355-362
[13] G. Aielli *et al.* , NIMA, 2006, **608**: page 246
[14] B. Bartoli *et al.* , Phys. Rev. D., 2011, submitted
[15] G. Di Sciascio *et al.* , these proceedings (226)