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Detection of anisotropies in the arrival directions of 600 GeV - 10 TeV cosmic rays with the ARGO-YBJ experiment

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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.

Key words. Extensive Air Showers – Cosmic Rays – Anisotropy – ARGO-YBJ

1. 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 Amenomori et al. (2007, 2009). They modelized it with a couple of intensity excesses in the hydrogen deflection plane, each of them $10° - 30°$ wide. Afterwards the Milagro collaboration claimed the discovery of two localized regions of excess 10-Tev cosmic rays Abdo et al. (2008). Regions "A" and "B", as they were named, are positionally consistent with the "skewed feature" observed by Tibet-ASγ and were parametrized as:

$$\begin{array}{lll} \text{region``A''}: & 117° \leq \text{r.a.} \leq 131° & 15° \leq \text{dec.} \leq 40° \\ & 131° \leq \text{r.a.} \leq 141° & 40° \leq \text{dec.} \leq 50° \\ \text{region``B''}: & 66° \leq \text{r.a.} \leq 76° & 10° \leq \text{dec.} \leq 20°. \end{array}$$

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

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search of cosmic-ray anisotropies in the southern emisphere ever (Abbasi et al. 2011). 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, because the gyroradius of cosmic rays is $r_{a.u.} = 100\,R_{\mathrm{TV}}$, where $r_{a.u.}$ is in astronomic units and R_{TV} is in TeraVolt.

As will be delt in later on, the excesses are $10° - 30°$ 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.

2. The ARGO-YBJ experiment

The ARGO-YBJ experiment Aielli et al. (2006) 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 Bartoli et al. (2011); Di Sciascio et al. (2011) guarantees angular resolution well below the angular scales dealt with in this paper.

3. Data analysis and results

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 $\delta \sim -20° \div 80°$.

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 (Fleysher et al. 2004), 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.

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 Abdo et al. (2008). 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.

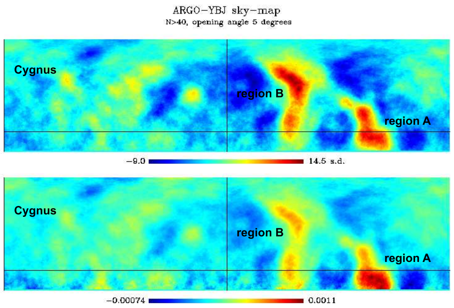

Fig. 1. ARGO-YBJ sky-map in celestial coordinates. Opening angle 5°. *Upper plot:* significance of the observation. *Lower plot:* relative excess with respect to the estimated background.

[1] This value is half that used by Abdo et al. (2008).

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 $195° \leq r.a. \leq 315°$ 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. 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 an-

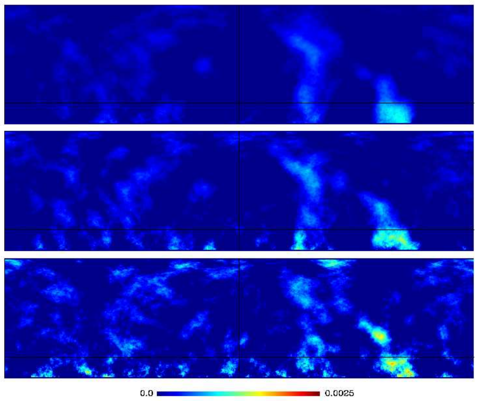

Fig. 2. Evolution of the cosmic ray intermediate scale features with the energy. The color scale spans 0 to 10^{-3}. See the text for details.

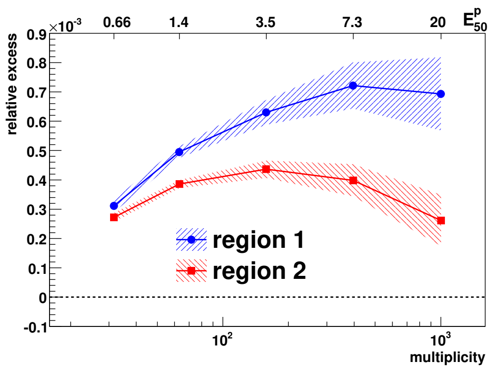

Fig. 3. Multiplicity spectrum of the region "A" and "B" excesses. The lower horizontal axis represents the number of fired strips. The vertical axis represents: the ratio between the events collected. The upper horizontal axis represents the median energy for proton-induced showers in TeV.

gular scale of 5° − 10° and what appears to be merged at lower energies seems to be well separated a factor 10 above (see region "A" for instance).

As a preliminary result, we computed the energy spectrum of the two most intense excesses, for which we the parametrization for the ARGO-YBJ data-set, so that all the observed excesses are included. Regions "A" and "B" become "1" and "2" respectively.

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 region "A" and "B". These aspects of the analysis are still under investigation.

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". If the explanation of the observed phenomena 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.

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