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Origin of cosmic rays of extreme energy

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Abstract. The origin of cosmic rays of extreme energy remains unknown. The data collected over the past few decades by the Pierre Auger Observatory and the Telescope Array indicate the presence of anisotropy in the distribution of their arrival directions, suggesting extragalactic astrophysical sources. However, the nature of these sources is still unsolved. The interaction with the CMB during propagation limits the origin of these particles to nearby sources (GZK effect). We investigate here the anisotropy of ultra-high-energy (UHE) cosmic rays ($\gtrsim 10^{18}$ eV) for two prominent classes of nearby extragalactic objects: starburst galaxies (SBG) and active galactic nuclei (AGN). These astrophysical objects provide the energy budget required to produce the observed flux of UHE cosmic rays and meet Hillas criterion.

1 Methods

For the propagation of UHE cosmic rays in the Galactic and extragalactic environments, we used the public simulation program CRPropa 3 [1]. For the Galactic magnetic field (GMF), we used the data-driven JF12 model [2, 3]. We assumed the extragalactic magnetic field (EGMF) as a Kolmogorov-type turbulent field with a correlation length of 216 kpc and a strength (RMS) of 1 nG [4]. The primary particles were first tracked through the EGMF from sources up to the edges of our galaxy. Then, the propagation in the GMF was addressed using the "lensing technique" [5]. Two different classes of extragalactic candidates were considered: the nearby SBG with a redshift $z < 0.03$ [6, 7] and the nearby AGN with a redshift $z < 0.07$ [8]. Each source was weighted with its radio luminosity as it is proportional to the non-thermal power. We considered two distinct mass compositions at injection. The first was a pure-proton composition, in agreement with the TA results [9]. The second was a mixed composition with five equal-abundance elements (^{1}H, ^{4}He, ^{16}O, ^{28}Si, ^{56}Fe), in agreement with the Auger results [10]. The injected spectrum was assumed to be a power law in energy:

$$\frac{\mathrm{d}N}{\mathrm{d}E} \propto E^{-\gamma} \exp\left(-\frac{E}{E_{\mathrm{cut}}}\right)$$

N is the number of particles at injection, E is the energy, γ is a spectral index and E_{cut} is an energy cutoff. The maximum energy (E_{max}) attainable by a source was fixed to 3×10^{20} eV [11]. Since the acceleration of cosmic rays is most likely of electromagnetic origin, E_{cut} and E_{max} were deemed rigidity-dependent.

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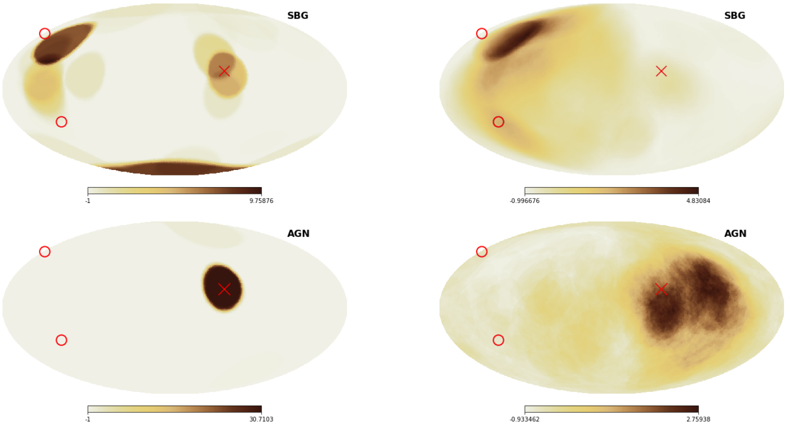

Figure 1. Mollweide projection of the skymap in galactic coordinates of the residual flux of the cosmic-ray arrival directions for the pure-proton composition (left) and the mixed composition (right). Also shown are the directions of event excesses observed by Auger (crosses) [12] and TA (circles) [13].

2 Results

We fixed the number of cosmic rays reaching the Earth in each run to 10^4. We set the minimum of energy at 50 EeV. The distributions of arrival directions were analysed using HEAPix [14], with a resolution of 49152 pixels. All the pixels were over-sampled over an angular scale of 20° (medium-scale anisotropy). The anisotropy is, as usual, established with respect to the isotropic expectation. The results (Fig. 1) indicate that the Auger excess can be attributed to either the NGC 4945 or Centaurus A (Cen A) as they both lie in the same direction. Likewise, the hotspot observed by TA [15] may be linked to the SBG M82. These three objects are all located within 4 Mpc from the solar system.

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