Anisotropy studies with the Pierre Auger Observatory

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Abstract. We report recent results from the Pierre Auger Observatory about the anisotropy of ultra-high energy cosmic ray arrival directions. We discuss the results on the search for a dipolar anisotropy at the EeV energy scale. Both the phase and the amplitude measurements of the first harmonic modulation in the right-ascension distribution are discussed. For cosmic rays with energies above 55 EeV, we present an update on the search for correlations between their arrival directions and the positions of active galactic nuclei from the Véron-Cetty and Véron catalog. Finally, we also discuss the results about the search for multiplets and the search for neutron point sources in the Galaxy.

1. Introduction

The search for anisotropies in the arrival directions of ultra-high energy cosmic rays (UHECRs) is crucial to understand their nature and origin. The ankle, a hardening of the spectrum of UHECRs at energies around 4 EeV (1 EeV=10\(^{18}\) eV) [1, 2], can be interpreted as the transition between Galactic and extragalactic cosmic rays [1, 3] or as the distortion due to \(e^\pm\) production from the interaction between extragalactic protons and photons of the Cosmic Microwave Background [4]. In both cases a dipolar modulation of the right ascension distribution of cosmic ray arrival directions is expected [5]. In the first scenario the amplitude of the dipole should increase with energy up to the ankle, reaching a level of few %, but predictions of the amplitude and orientation of the dipole depend on the source distribution and the considered magnitude of the Galactic magnetic field. In the second scenario a less than % level dipole is expected due to the Compton-Getting effect [6] and it would be constant with energy and with an orientation related to the relative movement of the Earth with respect to the “rest frame” of extragalactic cosmic rays. We report here on both phase and amplitude measurements of the first harmonic modulation in the right-ascension (RA) distribution and the corresponding upper limits obtained for the amplitudes. At the highest energies, cosmic rays are expected to be weakly deflected by Galactic and extragalactic magnetic fields, therefore their arrival directions should reflect the distribution of their sources in the sky. In 2007 the Pierre Auger Collaboration showed evidence of anisotropy in the arrival directions of ultra high energy cosmic rays at the 99% confidence level, considering the correlation of their arrival directions with the position of AGNs from the 12th edition of the catalog of quasars and active galactic nuclei by Véron-Cetty and Véron (VCV) [7]. An update of the correlation signal is reported in this proceeding. The
identification of the location of the sources of cosmic rays can also be inferred by searching for the alignment of several events (multiplets), since the deflections caused by magnetic fields are expected to be inversely proportional to the energy of cosmic rays. This method allows also to constrain the value of the Galactic magnetic field. The Pierre Auger collaboration searched for multiplets among detected events with energy above 20 EeV. The results obtained for this analysis are presented. Finally the Pierre Auger Collaboration explored also the possibility that events with energies around 1 EeV could be neutrons produced by accelerating sites in the Galaxy. The results about the search for Galactic neutron point-sources are discussed.

2. Search for sidereal modulation

The surface detector (SD) of the Pierre Auger Observatory [8] is sensitive, in the EeV energy range, to intrinsic anisotropies with amplitudes down to the level of 1%. To obtain such a sensitivity level, it is required to have enough statistics and also to determine the exposure of the detector with a corresponding accuracy. For this reason the systematic uncertainties due to the variations in the counting rate of events induced by changes of atmospheric conditions [9] and by the growth of the size of the array have been taken into account. Then, the amplitude and the phase of the first harmonic modulation are calculated using the standard Rayleigh method [10], slightly modified in order to take into account the non-uniform exposure to different parts of the sky [11]. For events with energy below 1 EeV, the detection efficiency of the surface detector depends on zenith angle and composition, which amplifies the detector-dependent variations in the counting rate. Consequently, below 1 EeV, the amplitude and the phase have been derived by calculating the event counting rate differences between Eastward and Westward directions (East-West method [12]), so that the effects due to the variation of the detection efficiency were ruled out. This method is less sensitive with respect to the Rayleigh one but it depends much less on the weather effects and the modulations of the exposure, which are quite large for the lower energies. The amplitude of the dipole as a function of the energy shows no evidence in favour of a significant anisotropy signal, so upper limits have been derived on the amplitude of the dipole [11]. They are shown in Figure 1, together with the results from the previous experiments: EAS-TOP, AGASA, KASCADE and KASCADE-Grande. Also shown are the predictions up to 1 EeV of two different Galactic magnetic field models with different symmetries (A and S) [5], the predictions for a purely Galactic origin of UHECRs up to a few tens of $10^{19}$ eV (Gal) [13], and the expectations from the Compton-Getting effect for an extragalactic component isotropic in

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**Figure 1.** 99% C.L. upper limits as a function of energy in independent energy bins, on the amplitude of an equatorial dipole obtained by the Auger observatory (see text).

**Figure 2.** Phase of the first harmonic as a function of energy. The dashed line, resulting from an empirical fit, is used in the likelihood ratio test (see text).
Figure 3. The most likely value of the degree of correlation $p_{data} = k/N$ as a function of the total number of time-ordered events (excluding those in the exploratory scan). The 68%, 95% and 99.7% C.L. intervals around the most likely value are shaded. The horizontal dashed line shows the isotropic value $p_{iso} = 0.21$, the full line shows the present fraction of correlating events, $p_{data} = 33 \pm 5\%$ for the full data set (excluding the exploratory scan), and the black points are averages of consecutive bins of 10 events.

Figure 4. Observed multiplets with 10 or more events in galactic coordinates. The size of the circle is proportional to the energy of the event. Plus signs indicate the positions of the potential sources for each multiplet. One decuplet is in fact three dependent decuplets that are formed by the combination of twelve events and the three corresponding reconstructions of the potential sources are shown.

the CMB rest frame (C-GXgal) [14]. The particular model with an antisymmetric halo magnetic field (A) is already excluded by the obtained upper limits as it is the 4\% anisotropy reported by AGASA. The measurement of the phase (see Figure 2) shows a smooth transition between a common phase of 270° (compatible with the right ascension of the Galactic Center $\alpha_{GC} = 268.4^\circ$), at energies below about 1 EeV, and another phase at $\alpha \simeq 100^\circ$ for higher energies. This is an interesting feature, as the phases are expected to be randomly distributed in case of independent samples with an isotropic distribution. The probability that the hypothesis of isotropy better reproduces our phase measurements compared to the alternative hypothesis has been calculated through a likelihood ratio test and it is found to be $\simeq 2 \cdot 10^{-3}$. It is worth to note that, if there is a weak anisotropy signal, a consistency of the phase measurement in ordered energy intervals is expected already at lower statistics than that required for the amplitude to significantly stand out of the background noise [15].

3. Search for correlation with nearby extragalactic matter

The analysis of correlation between the arrival directions of the highest energy events detected by the Pierre Auger Observatory and the positions of AGNs from the VCV catalog was based on an exploratory scan of the data. This revealed a strong correlation between events with energy above 55 EeV and those AGNs which are located within about 75 Mpc of the Earth and within an angular distance of 3.1°, and such a correlation signal was confirmed eventually by an independent data set [16, 17]. Then, successive data indicated a correlating fraction smaller than its early estimate [18]. In Figure 3 the most likely value of the degree of correlation $p_{data} = k/N$ (fraction of $k$ events correlating out of $N$), as a function of the total number of time-ordered events observed up to June 2011, is shown [19]. The latest value is (33±5)\% while 21\% is expected from an isotropic distribution. The cumulative binomial probability that an isotropic flux would yield 28 or more correlations is $P = 0.006$. This updated measurement with 84 events after the initial scan is a posteriori, and no unambiguous confidence level from
anisotropy can be derived from it. The cumulative number of events with $E \geq 55$ EeV as a function of angular distance from the direction of Cen A showed a maximum departure from the isotropic expectation for 19 arrival directions within $24^\circ$, while 7.6 arrival directions were expected if the flux were isotropic. In a Kolmogorov-Smirnov test, 4% of the realizations of 98 arrival directions drawn from an isotropic distribution have a maximum departure from the isotropic expectation greater than or equal to the maximum departure observed in data.

4. Search for multiplets of directionally-aligned events
The search for multiplets was performed for events detected by the Pierre Auger Observatory with an energy above 20 EeV [20]. Multiplets are found selecting those events aligned in the sky for which there is a correlation between their arrival direction and the inverse of their energy. The largest multiplet is one 12-plet and also two independent decuplets were found. The arrival directions in galactic coordinates of these multiplets are shown in Figure 4. The fraction of simulations of isotropically distributed events with at least one multiplet with 12 or more events is 6%, and the fraction having at least three multiplets with 10 or more events is 20%, so there is no statistically significant evidence for the presence of multiplets from actual sources.

5. Search for neutron point sources
Two analyses have been performed to constrain the neutron flux from Galactic sources in three energy bands: [1-2] EeV, [2-3] EeV, and $E \geq 1$ EeV. First, a blind search for localized excesses in the CR flux over the exposed sky was performed. The search was made comparing the number of observed events with that expected from an isotropic background, in top-hat counting regions matching the angular resolution of the instrument. Second, a stacking analysis was performed in the direction of bright Galactic gamma-ray sources detected by the Fermi LAT (100 MeV-100 GeV) and the H.E.S.S. (100 GeV-100 TeV) telescopes. Both methods found no significant excess so upper limits on the flux were derived for all parts of the sky. For energies above 1 EeV, the 95 % C.L. upper limit on the flux is less than 0.065 km$^{-2}$ yr$^{-1}$, corresponding to an energy flux of 0.13 EeV km$^{-2}$ yr$^{-1}$ $\simeq$ 0.4 eV cm$^{-2}$ s$^{-1}$ in the EeV decade, assuming an $1/E^2$ differential energy spectrum [21].

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