Abstract

The present work provides a detailed analysis of the large angular scale anisotropies of the arrival directions of the cosmic rays gathered by the surface detector of the Pierre Auger Observatory. The Observatory is located in Argentina and it is today the most complex and biggest detector of ultra-high energy cosmic rays. Its hybrid design combines two detection systems: the fluorescence telescopes and an array of surface detectors. The latter is a triangular grid of water Cherenkov stations.

The developments in this thesis cover the preparation of the optimized dataset for anisotropy searches, the estimation and correction of the spurious modulations associated to experimental conditions and finally the execution of procedures to reconstruct dipolar and quadrupolar anisotropies in the flux of cosmic rays in different energy intervals. The optimum dataset for anisotropy studies is the one in which all the systematic errors are corrected down to levels below the experimental uncertainties and the statistical uncertainties of the analysis method itself. The atmospheric conditions, such as pressure (P), temperature (T) or air-density ($\rho \propto P/T$) are examples of sources of systematic errors as they affect the development of the extensive air showers and its properties inferred from experiments on the Earth's surface. In this work, previous studies about the impact of the weather variations in reconstructing the air showers measured by the surface detector of the Auger observatory are improved and updated. Also the way to correct for these effects in the estimation of the energy of the primary cosmic ray is provided. The improvements with respect to the previous analysis include: increase in statistics that allows to perform the procedure at a higher energy threshold (10^{18} eV≡1 EeV) in which the detector is more efficient, improvement on the agreement between the model and the observed event rate, fits to the zenith angle dependence of the corrections (useful for the implementation in the algorithm for the official reconstruction of events) and finally a similar analysis for the smaller array, dedicated to detect lower energy cosmic rays, is carried out for the first time.

The chain of detection for the surface detector follows a trigger hierarchy. In the anisotropy analyses at large angular scales performed so far it was required that the events fulfill a strict trigger criteria, in which the station with the largest signal must be surrounded by six active neighbors at the time of detection (6T5). For this work the possibility of relaxing the above mentioned condition and also include events in which the hottest station has only five of its neighbors working is analyzed. It is found that for energies above 4 EeV the systematic effects that could be induced by relaxing the trigger condition are well below the statistical and systematic uncertainties of the reconstruction procedure itself. The number of events increases by $\sim 18\%$ after adopting the 5T5 criteria.

The estimation of the dipolar and quadrupolar components of the flux of cosmic rays is performed through the Fourier analysis of the rate of events in right ascension and azimuth for energies above 4 EeV and with more than 12 years of data. Events with zenith angles up to $80°$ are considered so that the 85% of the sky is covered. Also, the trigger condition is relaxed to 5T5. The amplitudes of the first harmonic in right ascension obtained for the two energy bins, 4 EeV $< E <$ 8 EeV and $E \geq 8$ EeV, are $0.5^{+0.6}_{-0.2}\%$ and $4.7^{+0.9}_{-0.7}\%$, respectively. In the lower energy bin the result is consistent with isotropy. On the other hand, in the interval above 8 EeV a significant amplitude is obtained, having a probability of arising by chance from an isotropic distribution of 2.6×10^{-8}. Penalizing for the fact that the search is done in two independent energy ranges, the present anisotropy has a significance of 5.4σ. Combining the first harmonic in right ascension with a similar one in azimuth the three-dimensional dipole components are reconstructed. The signal for $E \geq 8$ EeV is described by a dipole with a $6.5^{+1.3}_{-0.9}\%$ amplitude and pointing to the direction with galactic coordinates $(\ell, b) = (233°, -13°)$, i.e. $\sim 125°$ from the Galactic center which is indicative of an extragalactic origin of the cosmic rays with energies higher than 8 EeV. Including the second harmonics, the quadrupolar components are determined, none of which are significant. Subsequently, the energy range above 8 EeV is subdivided into three additional bins: [8,16] EeV, [16,32] EeV and $E \geq 32$ EeV, analyzing a possible evolution of the observed dipole with energy. The phases are not very different amongst the energy intervals and a tendency of an increasing amplitude with energy is found for $E > 4\,\text{EeV}$.

The analysis of the distribution of arrival directions of cosmic rays below 4 EeV, which is the threshold for full trigger efficiency, is exposed to higher systematic uncertainties due to the possible dependence of the efficiency with the arrival angle and the atmospheric conditions. In order to account for this effects the dependency of the detection efficiency with energy and zenith angle is parametrized and a correction of the atmospheric effects on the aforementioned efficiency is proposed. These corrections allow controlling the systematics to perform the Fourier analysis in right ascension at energies lower than the full efficiency threshold. Using the data collected by the two surface arrays of the Auger Observatory the component of the dipole in the equatorial plane is reconstructed for energies from ~ 0.03 EeV up to $E \geq 32$ EeV. Aside from the amplitude reported above 8 EeV none of the remaining energy intervals has a significant modulation of the flux. However, a phase transition is apparent from values close

to the Galactic center ($\alpha_d \simeq \alpha_{CG} = -94°$) at energies below 1 EeV to almost opposite directions ($\alpha_d \simeq 100°$) above 4 EeV.

Finally, the expected arrival direction distributions from simple scenarios of ultra-high energy cosmic ray sources are analyzed. The effects of the Galactic magnetic field on the anisotropies of the flux are discussed and compared with the observed anisotropies. In first place, the case of Galactic cosmic rays is considered. For that purpose it is assumed that the sources follow the distribution of the luminous matter in the Galaxy. The results are dependent of the energy to charge ratio E/Z and they are reported for some relevant values. The direction of the dipole is not compatible with the observed one above 8 EeV in any of the analyzed cases. Secondly, the effects on an extragalactic flux are studied: as an initial scenario it is assumed that the distribution entering the Galaxy halo is a pure dipole, the change in the direction and magnitude of this dipole due to the propagation through the Galactic magnetic field is determined for different values of E/Z. The second scenario adopts a distribution of sources following a catalog of galaxies and includes the effects of propagation through the extragalactic magnetic fields. Maps of expected flux for different energies are built. Afterwards, the direction of the dipole and the angular power spectrum C_ℓ up to $\ell = 20$ are estimated for the flux before and after traversing the Galactic magnetic field. Last, the dependence of the distribution of the arrival directions on the density of sources and their spatial distribution is studied.

Keywords: COSMIC RAYS, ANISOTROPY, MAGNETIC FIELD, FOURIER ANALYSIS