Abstract

STUDY OF THE ARRIVAL DIRECTIONS OF ULTRA-HIGH ENERGY COSMIC RAYS DETECTED BY THE PIERRE AUGER OBSERVATORY

This thesis is based on the analysis of the arrival directions of ultra-high energy cosmic rays ($E > 10^{18}\,\text{eV} \equiv 1\,\text{EeV}$) with the purpose of finding their astrophysical sources and obtaining information about the magnitude of the galactic and extragalactic magnetic fields that are traversed by cosmic rays on their path from their sources to Earth. To perform this analysis we used data gathered at the Pierre Auger Observatory, located in Malargüe, Argentina.

In particular we studied the case in which several events coming from the same source were detected (called 'multiplets') and we analyzed the possibility of locating the source position and extracting valuable information about the magnetic field along the line of sight towards it. We simulated randomly located sources in the sky and considered sets of events coming from them with a power law energy spectrum E^{-2} at the source, which was then modified according to the lensing effects expected in each sky direction. We propagated cosmic rays through a galactic magnetic field modeled with both regular and turbulent components that aim to reproduce the general characteristics of the observational results. The regular component was modeled with a spiral bisymmetric field symmetric with respect to the Galaxy's mid-plane (BSS-S) and for the turbulent component we used a Gaussian random field.

From the arrival directions and energies of the simulated events, we analyzed the expected correlation between the arrival direction and the inverse of energy. This correlation is due to the fact that cosmic rays are mostly charged particles and they are deflected by magnetic fields on their way through the Galaxy by a different amount depending on their energy and hence are observed at different arrival directions that are aligned in the sky according to their energy. The arrival direction at Earth $\vec{\theta}$ of a particle with energy E is related to the source direction $\vec{\theta}_s$ through $\vec{\theta} = \vec{\theta}_s + \frac{\vec{D}(\vec{\theta})}{E}$, with $\vec{D}$ the integral along the line of sight of the perpendicular component of the magnetic field $\vec{B}$ times the charge Ze of the particle: $\vec{D}(\vec{\theta}) = Ze \int_0^L \mathrm{d}\vec{l} \times \vec{B}(\vec{l})$. Therefore, from the arrival direction as a function of $1/E$ of the events, it is possible to reconstruct the source position and the integral of the perpendicular component of the magnetic field along the line of sight, performing a linear fit ($D(\vec{\theta}) \simeq D(\vec{\theta}_s)$, valid for small deflections) or a quadratic fit (next order in $1/E$). We analyzed the accuracy of both fits, comparing the reconstructed values with the original ones. To study the effect of experimental resolution in energy and position, we included Gaussian uncertainties in the energy and arrival direction of the simulated events of the magnitude of the resolution of the Pierre Auger Observatory. We showed that if ten events with energy above 30 EeV are detected coming from the same source, it would be possible to reconstruct the source position with an uncertainty of 0.8° and the integral of the perpendicular component of the magnetic field along the line of sight with an uncertainty of 0.8 μG kpc Z^{-1}, taking into account the experimental resolution. This work was published in Astroparticle Physics [1].

Moreover, we studied methods for the detection of multiplets in the realistic case that several events coming from the same source are superposed with background events (events not coming from that source). We considered events with energy above 20 EeV detected by the Pierre Auger Observatory and analyzed the different sets of events with the reconstruction methods explained before. To select the sets of events that could correspond to a same source and differentiate them from sets of background events we applied a cut in the linear correlation coefficient between the deflection angle u and the inverse of energy, $C(u, 1/E) > C_{\mathrm{min}}$, and a cut in the angular spread in the direction w that is orthogonal to the deflection, $W = \max(|w_i - \langle w \rangle|) < W_{\mathrm{max}}$. We obtained the optimal value for C_{min} y W_{max} using simulations of multiplets coming from sources and comparing the number of events that are retained when applying different values for the cuts with the significance of the multiplets. The significance was computed as the fraction of simulations of events with isotropic distribution in which an equal or larger multiplet satisfying the same cuts appears by chance. In this way, we determined that the best compromise between maximizing the signal from a true source and minimizing the background arising from chance alignments for the total number of events analyzed (~ 1500) is obtained for $C_{\mathrm{min}} = 0,9$ and $W_{\mathrm{max}} = 1,5°$. Applying these cuts in the data gathered by the Pierre Auger Observatory between 1st January 2004 and 31st December 2010 we found a multiplet with 12 events and two multiplets with ten events. For the correlated multiplets found, we reconstructed the position of the potential source and the integral of the orthogonal component of the magnetic field along the line of sight. We computed the probability that the multiplets were due to chance alignment of isotropic events (taking into account the exposure of the Observatory) and determined that the multiplets found in the data are not statistically

significant. Furthermore, we proposed a follow up strategy of the multiplets found with the purpose of determining if one of them corresponds to an actual source. We computed the probability that a correlated multiplet grows with background events so that we can determine the chance probability that the multiplets grow after n new events. These results are described in technical notes of the Pierre Auger Collaboration [2–4] and in an article with the full Collaboration in the author list which was published in Astroparticle Physics [5].

Another complementary line of study was to develop a method to detect secondary images of a source that can appear due to magnetic lensing effects. This effect causes that cosmic rays of the same energy from the same source can arrive at Earth from different directions. These secondary images could be detected due to the fact that their flux is strongly magnified near the critical energy in which they appear. We characterized their typical angular distribution with simulations and developed an algorithm to search for this kind of clustering in data. We also determined the minimum number of events that are required to detect an excess with probability of occurring by chance in an isotropic distribution of arrival directions smaller than 10^{-3} and we estimated an upper limit to the source density which is needed to be able to detect such a number of events from a source. Detecting an excess due to the appearance of multiple images of a source would allow to obtain information regarding the location of critical lines and the energy at which caustics appear that would be valuable in disentangling between different models for the galactic magnetic field. This work was published in Journal of Cosmology and Astroparticle Physics [6]. We applied the algorithm developed to events with energies above 9 EeV detected at the Pierre Auger Observatory from 1st January 2004 to 4th November 2011, taking into account the non-uniform exposure of the Observatory in the calculation of the significance. The largest excesses observed are not statistically significant.

Keywords: ULTRA-HIGH ENERGY COSMIC RAYS, PIERRE AUGER OBSERVATORY, GALACTIC MAGNETIC FIELD