PROCEEDINGS OF SCIENCE

Anisotropy studies with the Pierre Auger Observatory

R. M. de Almeida*
Universidade Federal Fluminense, EEIMVR, Volta Redonda, RJ, Brazil
E-mail: rmenezes@id.uff.br

for the Pierre Auger Collaboration
Observatorio Pierre Auger, Av. San Martín Norte 304, 5613 Malargue, Argentina
E-mail: auger_spokespersons@fnal.gov
Full author list at: http://www.auger.org/archive/authors_2018_10.html

The search for understanding the cosmos has led mankind to a deep investigation of the sky. Using telescopes that capture radiation in various wavelength ranges, we can assess the existence of planets, stars, galaxies, clusters of galaxies, etc. In addition to electromagnetic radiation, subatomic particles, such as nucleons, or atomic nuclei, that propagate from space to our planet, here defined as cosmic rays, carry information that is revealing about the Universe. In particular, for those with energies above 10^{18} eV called Ultra High Energy Cosmic Rays (UHECR), interactions with the Earth's atmosphere make it possible to estimate their energy and chemical composition as well as to relate their arrival directions with potential astrophysical sources. In this work we describe two recent results obtained by the Pierre Auger Collaboration related to anisotropy studies. These are the large-scale anisotropy observed in the arrival direction of the events detected with energies above 8 EeV and indications of anisotropy at intermediate scales for those with energies above 40 EeV.

Neutrino Oscillation Workshop (NOW2018)
9 - 16 September, 2018
Rosa Marina (Ostuni, Brindisi, Italy)

*Speaker.

1. Introduction

Ultra high energy cosmic rays (UHECR) are particles with energies above 1 EeV[1] that hit our atmosphere coming from space. There are many open questions about them, such as their chemical composition, sources and acceleration mechanisms. The Pierre Auger Observatory, located in Malargue, province of Mendoza, Argentina, is the largest cosmic-ray experiment in the world. It is designed to measure the energy, composition and arrival directions of cosmic rays above 10^{18} eV in order to unveil the astrophysical scenario behind such ultra high energy particles. Its configuration comprises a Surface Detector (SD), consisting of a set of 1,660 Cherenkov radiation stations (WCD - Water-Cherenkov Detector), distributed over 3,000 km^2 and surrounded by the fluorescence detector (FD - Fluorescence Detector), which comprises a total of 27 telescopes. The SD detects particles from atmospheric showers that hit the ground with an almost 100% duty cycle while the fluorescence telescopes measure the development of the extensive atmospheric shower focusing on the ultraviolet radiation generated by the interaction between the shower particles and the nitrogen molecules along their trajectory with a duty cycle of 13%. By means of the information collected by the FD, it is possible to determine the primary energy and the depth in the atmosphere in which the particle production of the shower reaches a maximum value, called X_{max}, a very important parameter associated with the primary particle composition.

Among the many very interesting results obtained by the Pierre Auger Collaboration, for the better understanding of this work, the reader is referred to the measurement of the suppression of the flux of cosmic rays with energies above 40 EeV [1] and the observation of an increasingly heavier composition for events with energies above the ankle, the region of the spectrum around 4 EeV which presents a very sharp change in its slope. In this work, we describe the recent results obtained by the Pierre Auger Collaboration associated with anisotropy in the arrival direction of the events.

2. Arrival Directions

The distribution of the arrival directions of the ultra high energy cosmic rays is the most important clue to the understanding of the origin of these particles. The Pierre Auger Collaboration has performed several anisotropy searches by using different techniques, namely, blind searches for flux excess, auto-correlation, correlation with astrophysical sources and with the directions of events detected by different experiments, as well as harmonic analysis. Among the different results, the large-scale anisotropy observed in the direction of the events with energies above 8 EeV is the most significant one obtained by the Pierre Auger Collaboration [2]. This study was performed by using events with energies above 4 EeV, exploring the region for which the SD is fully efficient up to zenith angles of 80°. With such a range of zenith angles, we cover 85% of the celestial sphere. A first harmonic analysis in the right ascension distributions of the events was applied to two energy bins, namely $[4,8]$ EeV and $E \geq 8$ EeV. The dipole amplitude obtained for the first bin is $r_\alpha = 0.005^{+0.006}_{-0.002}$, with a chance probability of arising from an isotropic distribution of 60%. On the other hand, for events with energies above 8 EeV, the amplitude of the first harmonic is $r_\alpha = 0.047^{+0.008}_{-0.007}$ with a chance probability of arising by fluctuation of an isotropic distribution of

[1] 1 EeV = 10^{18} eV

2.6×10^{-8}, corresponding to significance of 5.2 σ after statistical penalizations. The corresponding cosmic-ray flux is shown in the top panel of Figure 1. A clear dipole pattern can be seen with a reconstructed 3D dipole of 6.5% amplitude pointing to a Galactic coordinates $(l,b) = (233^\circ, -13^\circ)$, $\sim 125^\circ$ away from the Galactic center, supporting the hypothesis that the origin of these cosmic rays is extragalactic.

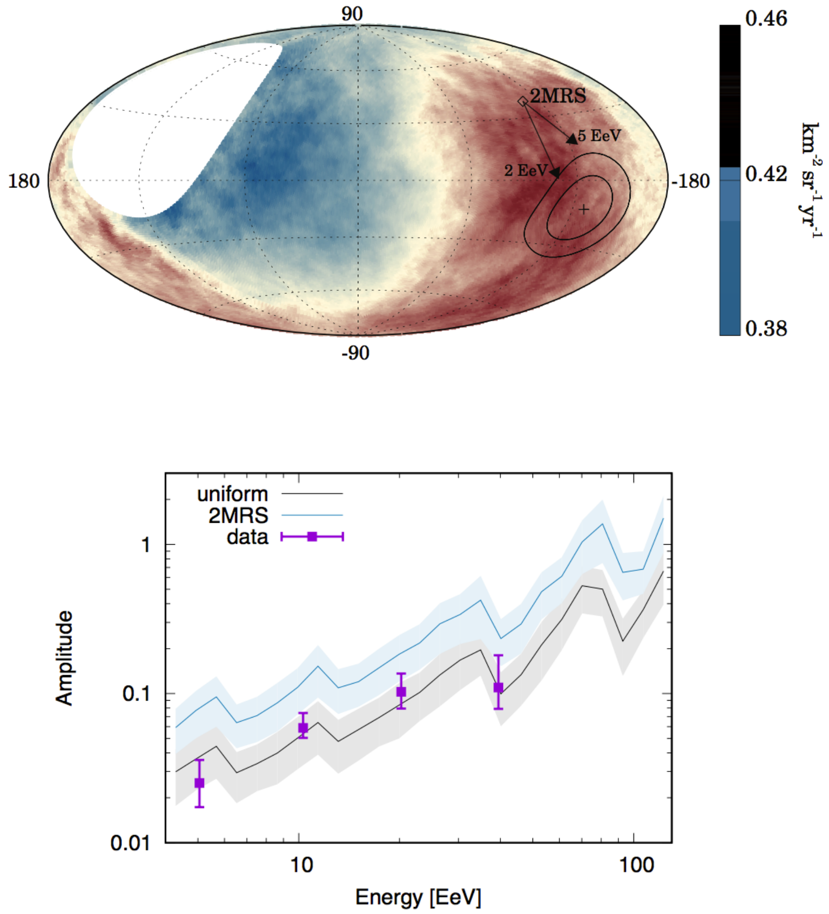

Figure 1: Top: measured cosmic-ray flux for events detected with energy above 8 EeV averaged on top-hat windows of 45°, in Galactic coordinates [2]. The direction of the reconstructed dipole is shown together with the 68% and 95% C.L. regions. The 2MRS dipole direction is also shown as well as cosmic-ray expectations from 2MRS sources, taking into account magnetic deflections. Bottom: evolution of the dipole amplitude as a function of energy as well as expectations from two different extragalactic source scenarios [3].

The dipole direction is $\sim 55^\circ$ away from the 2MRS dipole. Notice, however, that, as shown in Figure 1, the direction of the cosmic ray dipole resulting from the 2MRS galaxies after taking into account the deflection on the Galactic magnetic field (arrows point to dipole directions corresponding to two representative values of E/Z) would not be far from the one observed in the Auger data. A new analysis was performed in [3] by splitting the highest energy bin in three: [8,16] EeV, [16,32] EeV and $E \geq 32$ EeV. The reconstructed amplitude as a function of the energy together with expectations of scenarios in which extragalactic sources are uniformly distributed or following the observed galaxy distribution [4] are shown in the bottom side of Figure 1. The amplitude of the dipole increases with energy above 4 EeV, as expected by the predictions. Although there is no clear trend in the change of dipole direction as a function of energy, they are consistent with an extragalactic origin in all bins.

In a different analysis, a very interesting indication of anisotropy at intermediate scales for events with energies above 40 EeV was obtained in [5]. In this study, the analysis takes into account the flux of single sources, based on the assumption that the UHECR flux is proportional to the non-thermal electromagnetic flux. Thus, the arrival directions of the events detected by the Pierre Auger Collaboration were analyzed in comparison with nearby gamma-AGNs and starburst galaxies from the *Fermi*-LAT source catalogs. The two extragalactic gamma-ray populations used in this study are composed by 17 blazars and radio-galaxies with integral γ-ray fluxes used as a proxy for the UHECR flux and 23 starburst galaxies with a radio flux larger than 0.3 Jy. The attenuation of the flux due to energy losses in the propagation of the cosmic ray until Earth was also taken into account. The sky model is derived as a combination of isotropic and anisotropic components coming from the sources. The free parameters of the model are the fraction of events coming from the sources and a smearing angle that takes into account the average deflection in the cosmic-ray trajectory due to magnetic fields. The top panel of Figure 2 shows the test statistic (TS) based on the likelihood ratio between model and isotropy as a function of the energy.

The maximum of the test statistic evolution is found for 60 EeV for the AGNs and 39 EeV for the starburst galaxies, The best-fit parameters for the starburst galaxy case are 10% of anisotropic fraction and a smearing angle of 13°. The TS obtained is 24.9 corresponding to a significance of $\sim 4\sigma$. The corresponding values for the γ-ray AGN case are 7% and 7° with a TS of 15.2 ($\sim 2.7\sigma$). The bottom panel of Figure 2 presents the observed excess map for the starburst galaxy population considering events with energies above 39 EeV.

3. Future prospects

The Pierre Auger Observatory is undergoing a major upgrade phase called AugerPrime [6]. It consists in the deployment of scintillators on top of each SD together with the installation of an extra small photomultiplier in each water-Cherenkov detection to increase the dynamic range. Also, radio antenas and new electronics will be installed in the whole array. The main goal of the AugerPrime is to enhance the determination of nuclear mass composition exploiting the 100% duty cycle of the surface detectors. This will certainly help the searches for anisotropies since it will allow to restrict the analyses to less deflected light particles. Therefore, by considering the events that will be detected by the Pierre Auger Observatory in the next years, the expectations for improvements in our knowledge about the sources of the ultra high energy cosmic rays are very promising.

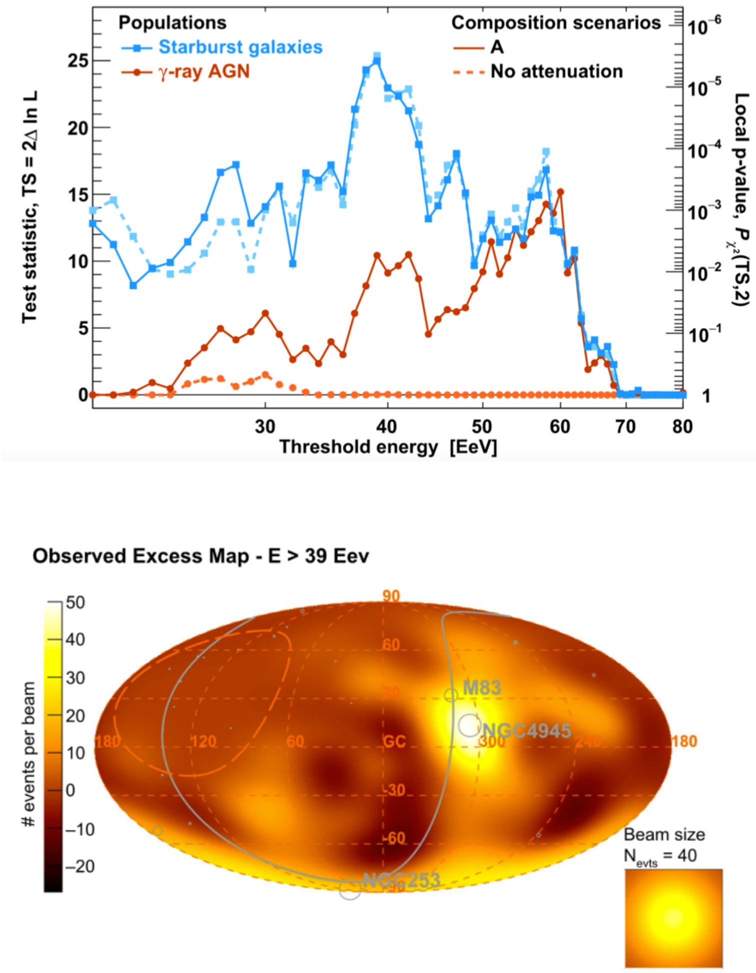

Figure 2: Top: test statistic (TS) as a function of the energy threshold for SBGs and γ-AGNs with and without take into account the attenuation of the intensity due to energy losses [5]. Bottom: observed excess map for starburst galaxies [5].

References

[1] J. Abhrahan et al. [Pierre Auger Coll.], PLB 685, 239 (2010)

[2] A. Aab et al. [Pierre Auger Coll.], Science 357 no.6537, 1266

[3] A. Aab et al. [Pierre Auger Coll.], ApJ, Vol 868, Number 1 (2018)

[4] D. Harari, S. Mollerach, E. Roulet, PRD 92, 063014 (2015)

[5] A. Aab et al. [Pierre Auger Coll.], ApJ, Vol 853:L29, Number 2 (2018)

[6] A. Aab et al. [Pierre Auger Coll.], "arXiv:1604.03637 [astro-ph.IM].