PROCEEDINGS OF SCIENCE

On ultra-high energy cosmic-ray arrival directions after ten years of operation of the Pierre Auger Observatory

Lorenzo Caccianiga* **for the Pierre Auger Collaboration**†

Laboratoire de Physique Nucléaire et des Hautes Énergies - CNRS, France

E-mail: lorenzo.caccianiga@gmail.com

Full author list: http://www.auger.org/archive/authors_2015_05.html

The Pierre Auger Observatory has gathered, in ten years of operation, an unprecedented number of extremely energetic cosmic-ray events. We present the latest results of searches for small to intermediate-scale anisotropies in the distribution of arrival directions of such events. We update the test based on the Véron-Cetty and Véron catalog, previously performed by the Pierre Auger Observatory on early data, and conclude that it does not yield a significant indication of anisotropy with the present data set. We then study the correlation of arrival directions with the position of nearby galaxies in the 2MRS catalog, of active galactic nuclei (AGNs) detected by Swift-BAT, of a sample of radio galaxies with jets and of the Centaurus A galaxy. None of the searches shows a statistically significant evidence of anisotropy. The two largest departures from isotropy found have a post-trial probability $\sim 1\%$. The first one is for cosmic rays with energy above 58 EeV that arrive within 18° of Swift-BAT AGNs closer than 130 Mpc and brighter than 10^{44} erg/s. The other one is for cosmic rays above the same energy threshold that arrive within 15° of the direction of Centaurus A.

XI Multifrequency Behaviour of High Energy Cosmic Sources Workshop
25-30 May 2015
Palermo, Italy

*Speaker.

†Observatorio Pierre Auger, Av. San Martín Norte 304, 5613 Malargüe, Argentina

1. Introduction

The origin of the ultra-high energy cosmic rays is still debated. The arrival directions of ultra-high energy cosmic rays contain information about their sources, if the sources are not distributed isotropically, and if the deflections of cosmic rays due to the magnetic fields are not too large. To reduce these constraints, it is interesting to study cosmic rays with energies above ~ 40 EeV: a suppression in the flux is observed at such energies [1] and it may be due to the Greisen Zatsepin and Kuz'min (GZK) [2, 3] effect, that would limit the distance of potential cosmic-ray sources. Such a *GZK horizon* would be of the order of a few hundred of Mpc for proton or iron-nuclei cosmic rays, and even lower for intermediate components: since the mass distribution of the universe is known to be anisotropic within such distances, if the sources of cosmic rays are astrophysical, they should be also anisotropically distributed at such energies. Since the so-called top-down models, accounting for sources in non-astrophysical scenarios, are severely constrained by the upper limits on ultra-high energy photon fluxes [4], we will not describe them here.

In the following, the latest arrival direction analyses performed on the largest dataset of cosmic rays with energy greater than 40 EeV is presented. This dataset is composed of the events detected at the Pierre Auger Observatory in more than 10 years of operation, from January 1^{st} 2004 to March 31^{st} 2014 with a total exposure of about 66,000 km^2 sr yr.

2. Dataset

The dataset used for the analyses that are presented in this paper is composed of 602 events with energy above 40 EeV measured between January 1^{st} 2004 and March 31^{st} 20144 by the Surface Detector (SD) of the Pierre Auger Observatory. The Pierre Auger Observatory is the largest ultra-high energy cosmic-ray detector in the world, consisting of an array of 1600 water Čerenkov detectors (stations) laid on a triangular grid with a spacing of 1500 m, spread over 3000 km^2 overlooked by 24 fluorescence telescopes (FD). A detailed description of the Observatory can be found in [5].

The dataset is a combination of 454 vertical events (with zenith angle $\theta < 60°$) and 148 horizontal events $60° < \theta < 80°$. In previous analyses, only vertical events were used, and the addition of more inclined events allows for a 30% increase in the number of events and for a higher coverage of the sky, now from a declination $\delta = -90°$ to $\delta = +45°$. The two datasets use a different selection and reconstruction procedure. The vertical events are selected if the station with the highest signal is surrounded by at least four other active stations. In addition, the reconstructed shower core position at the ground must lie within a triangle of contiguous operational stations. This event selection is updated with respect to previous analyses, and increases the number of vertical events by 14%, still ensuring an accurate event reconstruction. The selection of horizontal events requires five operational stations around the one with the highest signal. The ground estimator for the energy determination is the fitted signal at 1000 m from the shower axis for the vertical events, whereas in the horizontal reconstruction it involves the muon content relative to a simulated proton shower with energy 10^{19} eV. In both cases, the final energy estimation is done through the cross-calibration with the Fluorescence Detector that provides a quasi-calorimetric measurement.

PoS(MULTIF15)026

For the energies considered in this work, the detection and selection efficiency are 100% for both datasets. The exposure, determined only by the geometry of the array, amounts to 51,753 km^2 sr yr for the vertical sample and 14,699 km^2 sr yr for the horizontal one.

For all of the events in the dataset the angular resolution, defined as the 1σ radius around the true arrival direction, is better than 0.9° [6]. The statistical uncertainty in the energy determination is better than 12% for the energies considered here [7, 8] and the systematic uncertainty in the absolute energy scale is 14%. As a consequence of the recent update of the absolute energy scale [8], the energy threshold of 55 EeV used in our previous publication [9] now corresponds to approximately 53 EeV.

3. Cross-correlation with astrophysical sources

The most recent results of the Auger Observatory on anisotropy in the arrival directions of the highest-energy cosmic rays were described in detail in a recent publication [10]. There, in addition to the results summarized here, details were also presented on different searches for intrinsic correlations and correlations with astrophysical structures such as the Galactic Plane. In this paper we focus on the results of correlation with astrophysical catalogs.

Note on the anisotropy test with the Véron-Cetty and Véron (VCV) catalog

In a previous analysis, we searched for correlation of cosmic-ray arrival directions with the Véron-Cetty and Véron 2006 catalog of AGNs [11]. We measured the number of events above a certain energy threshold $E_{\rm th}$ within a certain angular distance Ψ from an AGN within a certain distance D, and compared to the numbers expected assuming isotropy. We performed an initial scan over the parameters with vertical events collected between January 1^{st} 2004 and May 26^{th}2006, and found the most significant excess at $E_{\rm th} = 57$ EeV, $\Psi = 3.1°$ and $D = 75$ Mpc. Using this set of parameters on subsequent independent data, we found a correlation fraction of 61%, with a 1.7×10^{-3} probability of happening by chance from an isotropic distribution [12]. With data up to the end of 2009, the correlation fraction was found to be much lower (38^{+7}_{-6})% [9]. With the current vertical data set, the correlation fraction is found to be $(28.1^{+3.8}_{-3.6})$%, only 2σ above the fraction expected from isotropy, that is 21%. We conclude that, with current data, this test does not provide a significant indication of anisotropy.

3.1 Selected astrophysical catalogs

In the following sections we show the results of a search for possible correlations of cosmic-ray arrival directions with the position of nearby extragalactic sources. We use three catalogs of candidate sources that have an almost uniform coverage and that are complete above a given luminosity: the 2MRS catalog [13] (catalog of galaxies), the Swift-BAT [14] (X-ray catalog of AGNs), and a catalog of radio galaxies with jets that was compiled in [15].

The 2MRS catalog is obtained in the infrared and maps the local distribution of galaxies, which could be associated with the location of pulsars, magnetars or gamma-ray bursts. The catalog is complete at the 97.6% level for magnitudes brighter than K_s =11.75, and contains $\sim 37,000$ galaxies within a distance of 200 Mpc and $\sim 16,000$ galaxies within 100 Mpc.

The Swift-BAT catalog contains 705 objects identified as AGNs, detected in X-rays after 70 months of operation. All these objects have a measured redshift. For a flux of 13.4×10^{-12} erg cm^{-2} s^{-1} in the $14 - 195$ keV range, the catalog is complete for 90% of the sky. There are 296 AGNs in this catalog within 200 Mpc and 160 within 100 Mpc.

The last catalog is a compilation from the 1.4 GHz NRAO VLA Sky Survey [16] and the 843 MHz Sydney University Molonglo Sky Survey [17] produced by Van Velzen et al. [15]. The catalog is nearly complete for fluxes above 289 mJy at 843 MHz and 213 mJy at 1.4 GHz, and contains 205 objects within a distance of 200 Mpc, and 56 within 100 Mpc.

The Swift-BAT and the radio-galaxy catalogs overlap by only 5%: the majority of the galaxies in the Swift-BAT catalog are of spiral type, whereas the radio galaxies are mostly elliptical.

3.2 Cross-correlation with flux-limited catalogs

The cross-correlation analysis consists in counting the number of pairs of event-candidate sources separated by less than a given angle. To find an excess, we compare the number of pairs obtained in data with the expectation from simulations assuming isotropy. We scan over three parameters: the minimum energy of events $E_{\rm th}$, from 40 EeV (where 1 EeV = 10^{18} eV) up to 80 EeV in steps of 1 EeV; the angular separation ψ, between 1° and 30° in steps of 0.25° up to 5° and steps of 1° up to 30°; and the maximum distance of the sources D, from 10 Mpc up to 200 Mpc in steps of 10 Mpc.

For each value of these parameters we compute the fraction f of simulations assuming isotropy having an equal or higher number of pairs than the data, and search for its minimum $f_{\rm min}$. The associated post-trial probability P is computed as the fraction of isotropic realizations that lead to a lower or equal value of $f_{\rm min}$ under the same scan.

The minima found in this way are summarized in table 1, top three lines. We note that the minimum value of P is 6%, thus not significant. The behavior of f and P for the scan performed on the Swift-AGNs catalog is shown in figure 1, left panel, as a function of D: we notice the minimum at 80 Mpc. In the right panel, the behaviour of f as a function of $E_{\rm th}$ and Ψ is shown for $D = 80$ Mpc. The minimum is indicated by a white cross.

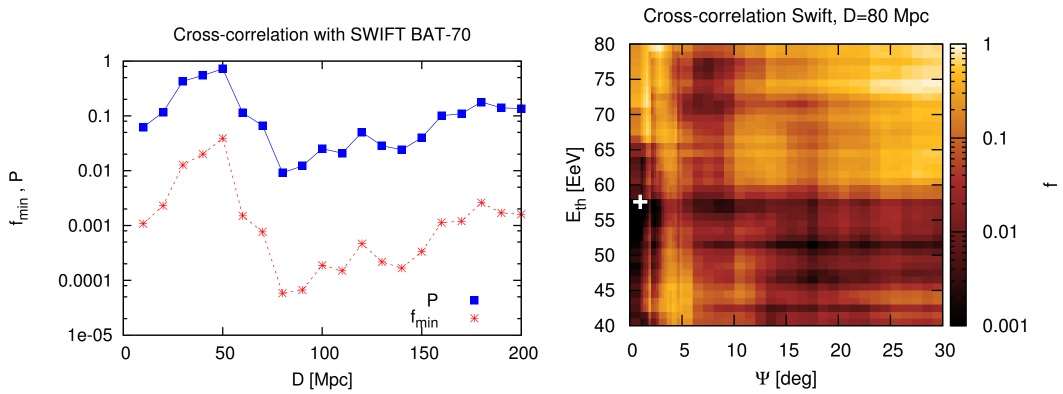

Figure 1: Cross-correlation of events with the AGNs in the Swift-BAT catalog. The left panel shows the values of $f_{\rm min}$ and P as a function of the maximum distance D to the AGNs considered. The right panel shows the results of the scan in ψ and $E_{\rm th}$ for the value $D = 80$ Mpc corresponding to the minimum values in the left plot. From [10].

3.3 Cross-correlation with bright AGNs

We performed a scan similar to the one presented in the previous section for the radio galaxies and Swift-AGNs catalogs, this time scanning also on the minimum luminosity $\mathscr{L}_{\rm min}$. For the Swift-BAT AGNs we used the luminosity $\mathscr{L}_{\rm X}$ measured in the X-ray band, scanning from 10^{42} to 10^{44} erg/s, considering three logarithmic steps per decade, for a total of 7 luminosity values. For the radio galaxies, we used the radio luminosity computed at 1.1 GHz, scanning from 10^{39} to 10^{41} erg/s, again with three logarithmic steps per decade.

Results of this scan are shown in table 1, in the fourth and fifth lines. We can see that the minimum value of P is obtained with the Swift-AGNs, where it reaches $f_{\rm min} = 2 \times 10^{-6}$ for $D = 130$ Mpc and $\mathscr{L} > 10^{44}$ erg/s, with a threshold energy of $E_{\rm th} = 58$ EeV and an angular distance $\Psi = 18°$. For these parameters, 62 pairs are observed between 155 cosmic rays and 10 AGNs while 32.8 are expected from isotropy. The behavior of f as a function of D and $\mathscr{L}$, and $E_{\rm th}$ and ψ is shown in the left and right panels of figure2, respectively. The minimum found is marked with a white cross.

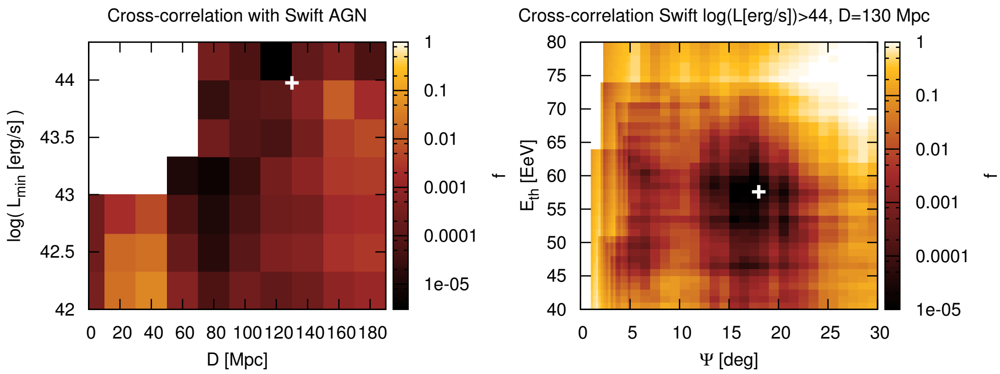

Figure 2: Cross-correlation of events with the AGNs in the Swift catalog as a function of D and $\mathscr{L}_{\rm min}$ (left panel) and detail of the scan in Ψ and $E_{\rm th}$ for the minimum found (right panel).

4. The Cen A region

Centaurus A is the closest radio-loud active galaxy, and is a natural candidate source for the acceleration of high-energy cosmic rays. The Centaurus cluster, which contains a large number of galaxies, lies at a distance of 50 Mpc and is approximately in the same direction as Cen A. We search for a correlation between the arrival directions of cosmic rays and the location of Cen A, counting the number of events within an angular radius Ψ between 1° and 30° for an energy threshold ranging from 40 to 80 EeV. The maximum excess is found where the fraction f of simulations assuming isotropy that give a higher or equal number of events than the data is minimum. The minimum of this fraction is found to be $f_{min} = 2 \times 10^{-4}$ for $E_{\rm th} = 58$ EeV and $\Psi = 15°$, where 14 events are observed while 4.5 are expected. The left panel of figure 3 shows the fraction f as a function of $E_{\rm th}$ and Ψ, with the minimum indicated with a white cross. The right panel shows the number of events above this threshold as a function of the angular distance from Cen A for the whole angular range, indicating also the 68, 95 and 99.7% intervals obtained from simulations assuming isotropy. The penalized probability to find a smaller $f_{\rm min}$ in simulations assuming isotropy

PoS(MULTIF15)026

under the same scan is 1.4%. It is also worth noting that, when searching for intrinsic anisotropies in the distribution of arrival directions of cosmic rays with energies above 40 EeV, by looking at excesses in circular windows over the exposed part of the sky (see [10] for details), the largest excess, though not significant, is close to the position of Centaurus A.

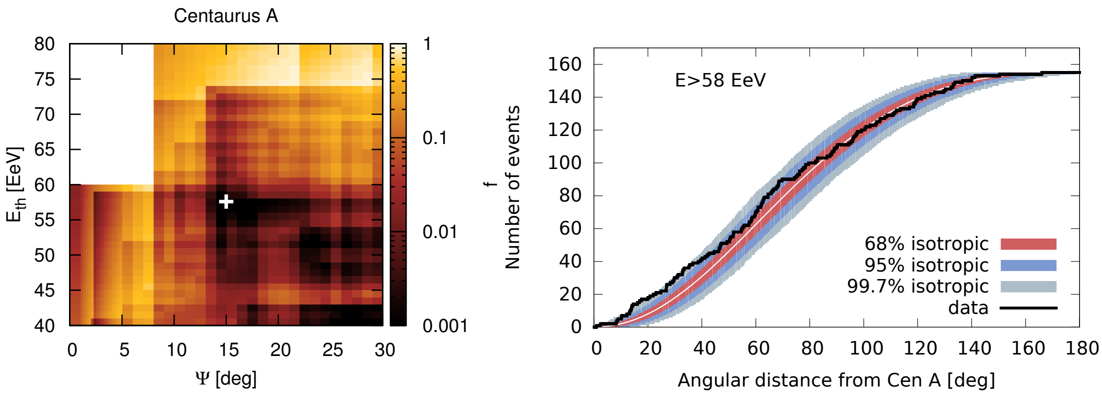

Figure 3: Correlation of events with the Cen A radio galaxy as a function of the angular distance and the energy threshold, $E_{\rm th}$ (left panel). The right panel shows the cumulative number of events for the threshold $E_{\rm th} = 58$ EeV, exploring the whole angular range. From [10].

Objects	$E_{\rm th}$ [EeV]	Ψ [°]	D [Mpc]	$\mathscr{L}_{\rm min}$ [erg/s]	$f_{\rm min}$	P
2MRS galaxies	52	9	90	-	1.5×10^{-3}	24%
Swift AGNs	58	1	80	-	6×10^{-5}	6%
Radio galaxies	72	4.75	90	-	2×10^{-4}	8%
Swift AGNs	58	18	130	10^{44}	2×10^{-6}	1.3%
Radio galaxies	58	12	90	10^{40}	5.6×10^{-5}	11%
Centaurus A	58	15	-	-	2×10^{-4}	1.4%

Table 1: Summary of the parameters of the minima found in the cross-correlation analyses.

5. Discussion and conclusions

We studied the distribution of arrival directions of the highest-energy cosmic rays observed by the Pierre Auger Observatory. A first test with the VCV catalog, updating previous studies, leads to a non-significant excess with respect to an isotropic distribution of events. We performed a cross-correlation search with nearby (within 200 Mpc) sources from three complementary astrophysical catalogs, together with a specific analysis of the arrival directions around the position of Cen A. The results are summarized in Table 1. The penalized probabilities P accounting for the scan on parameters are all of the order of a few percent, reaching the $\sim 1\%$ level when selecting only the brightest AGNs of the Swift-BAT catalog or with the Cen A radio galaxy. We note also that all minima, although not statistically significant, occur for a maximum distance $D \sim 80-90$ Mpc.

References

[1] A. Schulz for the Pierre Auger Collaboration. The measurement of the energy spectrum of cosmic rays above 3×10^{17} eV with the Pierre Auger Observatory. *Proceedings of the 33rd ICRC, Rio de Janeiro, Brazil*, 2013 `http://www.cbpf.br/~icrc2013/papers/icrc2013-0769.pdf`.

[2] K. Greisen. End to the Cosmic-Ray Spectrum? *Physical Review Letters*, 16(17):748–750, April 1966.

[3] G.T. Zatsepin and V.A. Kuz'min. Upper limit of the cosmic-ray spectrum. *Zh. Eksp. Teor. Fiz., Pis'ma Red.*, 4(3):114–117, 1966.

[4] The Pierre Auger Collaboration. An upper limit to the photon fraction in cosmic rays above 10^{19} eV from the Pierre Auger Observatory. *Astroparticle Physics* ,27 (2007) 155–168.

[5] The Pierre Auger Collaboration. The Pierre Auger Cosmic Ray Observatory. *Nuclear Instruments and Methods in Physics Research Section A: Accelerators, Spectrometers, Detectors and Associated Equipment*, Accepted for publication 2015.

[6] C. Bonifazi, A. Letessier-Selvon, E. M. Santos, the Pierre Auger Collaboration, et. al. A model for the time uncertainty measurements in the Auger surface detector array. *Astroparticle Physics*, 28(6):523–528, 2008.

[7] The Pierre Auger Collaboration. Reconstruction of inclined air showers detected with the Pierre Auger Observatory. *JCAP*, 1408(08):19, 2014.

[8] V. Verzi for the Pierre Auger Collaboration. The energy scale of the Pierre Auger Observatory. *Proceedings of the 33rd ICRC, Rio de Janeiro, Brazil*, 2013 `http://www.cbpf.br/~icrc2013/papers/icrc2013-0928.pdf`.

[9] The Pierre Auger Collaboration. Update on the correlation of the highest energy cosmic rays with nearby extragalactic matter. *Astroparticle Physics*, 34(5):314–326, 2010.

[10] The Pierre Auger Collaboration. Searches for anisotropies in the arrival directions of the highest energy cosmic rays detected by the Pierre Auger observatory. *The Astrophysical Journal*, 804(1):15, 2015.

[11] M.-P. Véron-Cetty and P. Véron. A catalog of quasars and active nuclei: 12th edition. *A&A*, 455(2):773–777, 2006.

[12] The Pierre Auger Collaboration. Correlation of the highest-energy cosmic rays with nearby extragalactic objects. *Science*, 318(5852):938–943, 2007.

[13] J. P. Huchra, L. M. Macri, K. L. Masters, T. H. Jarrett, P. Berlind, M. Calkins, A. C. Crook, R. Cutri, P. Erdo Ugdu, E. Falco, et al. The 2MASS Redshift Survey description and data release. *The Astrophysical Journal Supplement Series*, 199(2):26, 2012.

[14] W. H. Baumgartner, J. Tueller, C. B. Markwardt, G. K. Skinner, S. Barthelmy, R. F. Mushotzky, P. A. Evans, and N. Gehrels. The 70 month swift-BAT all-sky hard X-ray survey. *The Astrophysical Journal Supplement Series*, 207(2):19, 2013.

[15] S. Van Velzen, H. Falcke, P. Schellart, N. Nierstenhöfer, and K.H. Kampert. Radio galaxies of the local universe. *Astronomy & Astrophysics*, 544:A18, 2012.

[16] J. J. Condon, W. D. Cotton, E. W. Greisen, Q. F. Yin, R. A. Perley, G. B. Taylor, and J. J. Broderick. The NRAO VLA sky survey. *The Astronomical Journal*, 115(5):1693, 1998.

[17] T. Mauch, T. Murphy, H. J. Buttery, J. Curran, R. W. Hunstead, B. Piestrzynski, J. G. Robertson, and E M Sadler. SUMSS: a wide-field radio imaging survey of the southern sky–II. The source catalog. *Monthly Notices of the Royal Astronomical Society*, 342(4):1117–1130, 2003.

PoS(MULTIF15)026