Cosmic Ray Origin and Anisotropy Measurement by the Pierre Auger Observatory

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Summary. —   Recently the Pierre Auger Observatory has observed a dipolar anisotropy of amplitude $\simeq 6.5\%$ above 8×10^{18} eV that is unrelated to the Galactic plane. While the significance is largest above 8×10^{18} eV, the cosmic ray data indicate a growth of the dipolar amplitude from 4×10^{18} eV to 3.2×10^{19} eV and beyond. Furthermore, above 4×10^{19} eV, indications have been found for intermediate-scale anisotropies associated with extragalactic gamma-ray sources. Apart from those indications no other significant anisotropies are seen. We review these observations and discuss their relevance for the origin of ultra-high energy cosmic rays.

1. – Introduction

Even after more than a hundred years of research the origin and the sources of cosmic rays are still not known beyond doubt. This is in particular true for ultra-high energy cosmic rays (UHECRs) in the energy range above $\sim 10^{17}$ eV. Ideally, sources and their locations could be identified by observing "hot spots" in the sky, perhaps corrected by some moderate deflection due to Galactic and extragalactic magnetic field. However, the UHECR sky is surprisingly isotropic, and only recently have clear indications of anisotropies been identified, albeit not in the form of localised "hot spots", but rather on intermediate and large angular scales corresponding to small order multipoles. In the present contribution we briefly summarise the current status of UHECR anisotropy observations and their relevance for building astrophysical models for the sources and their spatial distributions.

2. – Anisotropy Measurements

Here we briefly summarise recent experimental results on UHECR anisotropy, mainly from the Pierre Auger Observatory, which consists of roughly 1600 surface detectors covering an area of about $3000\,\mathrm{km}^2$, overlooked by 27 fluorescence detectors located in 5 buildings on the periphery of the array, located in the province of Mendoza, Argentina.
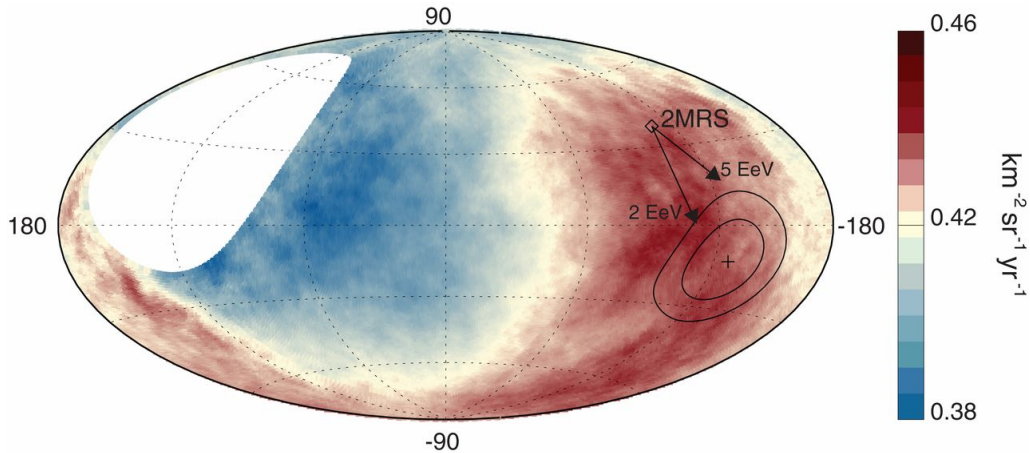
Fig. 1. – The UHECR flux observed above 8×10^{18} eV in Galactic coordinates, smoothed with a top-hat function with radius $45°$. The Galactic center is located at the origin. The measured best fit dipole direction is marked by the cross, and the contours delimit the 68% and 95% confidence level regions. The foot of the arrows mark the dipole direction in the 2MRS galaxy distribution and their heads indicate the amount of deflection of the 2MRS model for cosmic rays of rigidity $E/Z = 5$ EeV and 2 EeV, respectively, as expected in the Galactic magnetic field model from ref. [2]. From ref. [1].

The field of view covers about 85% of the celestial sphere and the total exposure collected for the studies below is of the order of 10^5 km^2 sr yr.

A recent analysis by the Pierre Auger Observatory revealed the first statistically convincing anisotropy of ultra-high energy cosmic ray arrival directions at energies above 8×10^{18} eV [1]. As shown in fig. 1, it is well described by a dipole of amplitude $6.5^{+1.3}_{-0.9}\%$ pointing into the direction $(l, b) = (233°, -13°)$ in Galactic coordinates and has a statistical significance of about 5.2σ. Importantly, this implies that the UHECR sources at those energies in all likelihood have to be extragalactic because, even when taking into account deflection in Galactic magnetic fields, the dipolar direction of the source distribution is far from the Galactic center, as is also demonstrated by fig. 1. Also, and to some extent independently of more extreme galactic magnetic field models which could shift the dipole of the source distribution closer to the Galactic center, a Galactic origin would tend to predict larger dipole amplitudes [3].

Although statistical significances for anisotropies at other energies are smaller, a subsequent analysis revealed a dipole amplitude growing with energy E as $E^{0.79\pm0.19}$ above 4×10^{18} eV [4].

Furthermore, in ref. [5] a correlation study has been performed between cosmic ray arrival directions and two catalogues of possible source candidates, namely 17 bright nearby active galactic nuclei detected by the Fermi LAT satellite detector, and 23 nearby starburst galaxies. It was assumed that the cosmic ray intensity is roughly proportional to the detected $\gamma-$ray flux or the observed 1.4 GHz radio flux, respectively. As free parameters were fitted the smearing angle relative to the source directions and the fraction of anisotropic cosmic rays being caused by the model. A lower energy threshold was optimised to maximise the correlation signal, with the respective penalty taken into account through Monte Carlo simulations. The strongest signal, at a significance of about 4σ,
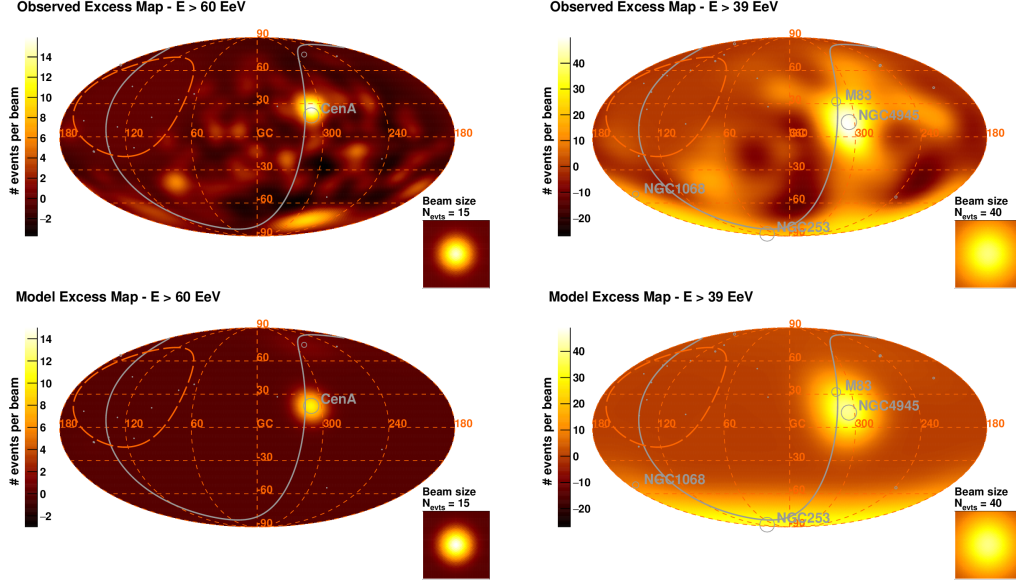
Fig. 2. – Skymaps of the excess fluxes above an isotropic background for the observed (top panels) and the source model predictions (bottom panels) obtained with the best-fit parameters for the gamma-ray AGNs (left panels, above 6×10^{19} eV) and for the starburst galaxies (right panels, above 3.9×10^{19} eV), in Galactic coordinates. The gray line indicates the supergalactic plane and the limit of the field of view of the Pierre Auger Observatory lies within the dashed red line. The insets labeled as "beam size' show the signal for a particular number of events and the respective smearing angle. From ref. [5].

occurs for starburst galaxies above $\simeq 3.9 \times 10^{19}$ eV, with correlating fraction of $\simeq 10\%$ within a correlation angle of $12 - 14°$, i.e. at intermediate scales. Some of these results are shown in fig. 2.

Apart from the dipole no statistically significant higher multipoles have been detected by the Pierre Auger Observatory so far [6, 4]. However, a "warm spot" within an angular radius of $\simeq 15°$ around the nearby radio galaxy Centaurus A has been observed above 5.8×10^{19} eV with a post-trial significance of $\simeq 3.2\sigma$ [7].

In the Northern hemisphere the Telescope Array has accumulated evidence for an intermediate scale anisotropy for UHECR arrival directions in the form of a deficit at energies $10^{19.2}$ eV $\leq E \leq 10^{19.75}$ eV and an excess above $\simeq 10^{19.75}$ eV, which is also known as the "hot spot" [8]. There are also common anisotropy analyses between the Telescope Array and Pierre Auger Observatory [9, 10] which together cover the whole sky and allow in particular, one to search for multipolar moments and the angular power spectrum. Apart from a weak hint for a dipolar anisotropy, no significant deviations from anisotropy has been found yet in this joint analysis.

For a comprehensive recent review of cosmic ray anisotropies see also ref. [11].

3. – Interpretation and Open Questions

In the following we present a few general remarks on the implication of observed cosmic ray anisotropies.

We first remind the reader of the so-called propagation theorem, which is a consequence of the Liouville theorem and in the context of UHECRs was emphasised in ref. [12]. It states that a homogeneous distribution of sources with equal properties and nearest neighbour distances smaller than other relevant length scales in the problem such as energy loss length and propagation/diffusion length within the source activity time scale gives rise to a universal/isotropic flux spectrum that does not depend on the propagation mode and thus on the magnetic field properties.

This can be seen in probably the easiest way in the back-tracking picture: The differential flux in the direction characterised by the unit vector $\mathbf{n}$ at observer position $\mathbf{r}_0$ is given by

$$(1) \qquad j(E_0, \mathbf{r}_0, \mathbf{n}) = \int_{t_0}^{t_{\max}} dt \dot{\rho} \left[E(t), t, \mathbf{r}(t, \mathbf{n}) \right] ,$$

where $\dot{\rho}(E, t, \mathbf{r})$ is the differential injection rate at energy E, time t, and location $\mathbf{r}$, $\mathbf{r}(t, \mathbf{n})$ is the back-tracked trajectory with the initial conditions $\mathbf{r}(t_0, \mathbf{n}) = \mathbf{r}_0$, $\dot{\mathbf{r}}(t_0, \mathbf{n}) = \mathbf{n}$ and $E(t)$ with $E(t_0) = E_0$ is the back-tracked energy. For stochastic energy losses and interactions one has to average over trajectories with equal initial conditions.

Clearly, if $\dot{\rho}$ only depends on E and t and not on location $\mathbf{r}$, then the flux neither depends on the shape of the trajectories nor on direction, but only on energy, and thus is universal. This implies that neither detected spectrum nor composition can depend on propagation mode and intervening magnetic fields and the flux has to be isotropic.

This also applies to secondary fluxes such as neutrinos and gamma-rays because their fluxes only depend on the time-integrated interaction rates (and energy loss rates) which are location independent.

An exception to this argument occurs if the observer is moving with respect to the large scale cosmic frame relative to which the sources are at rest on average. In this case the Doppler effect induces a shift between the energy measured in the source and the observer frame which induces a dipole with amplitude of the order of the relative velocity in units of the velocity of light. This is known as Compton-Getting effect. Its predicted value is, however, about a factor 10 lower than the observed dipolar amplitude [13] and thus cannot explain it.

As a result, to be sensitive to the propagation mode, magnetic field structure etc. requires discrete, inhomogeneous source distributions with nearest-neighbour distances larger than energy loss length and/or propagation distance within the characteristic source activity timescales, corresponding to an upper bound on the source density. Quantifying this upper bound requires detailed Monte Carlo simulations.

On the other hand, the absence of a significant two-point correlation of UHECR arrival directions gives a lower limit of $\simeq 6 \times 10^{-6} \, \mathrm{Mpc}^{-3}$ [14] on the effective number density of the sources, as well as a corresponding upper limit of $\simeq 5 \times 10^{43} \, \mathrm{erg \, s}^{-1}$ on the effective average source luminosity [15], for uniformly distributed sources, and somewhat stronger bounds for sources following the local matter distribution [14]. For intermittent sources these quantities are interpreted as the total energy released divided by a time scale T and the rate per volume times T, for an assumed delay time of $T \simeq 3 \times 10^5$ yr.

An interesting argument on the energy dependence of cosmic ray anisotropies has been made by Lemoine, Waxman et al. [16, 17]: Since, in the absence of significant energy losses, propagation only depends on cosmic ray rigidity E/Z, if at energies $> E$ an anisotropy were seen in cosmic rays of characteristic nuclear charge Z, then at energies $> E/Z$ an anisotropy should be detected in protons, with a significance even larger than

above energy E, mainly because of the larger event rate at lower energies in a cosmic ray flux that overall is relatively steeply falling with increasing energy. Since the Pierre Auger Observatory does see a mass composition that is already significantly heavier than protons above 8×10^{18} eV, see e.g. refs. [18, 19] and ref. [15] for a review, it remains to be seen how, and if, this can be made consistent with smaller observed statistical significances of anisotropies at lower energies. Note that the scenario by Lemoine, Waxman et al. [16, 17] of dipolar significance increasing with decreasing energy is not in contradiction with an intrinsic dipole strength increasing with energy, as predicted by some models [20, 21] and suggested by observations [4]: If the dipole increases as E^{α} and the integral flux scales as E^{-2}, then the number of events associated with the dipole scales as $E^{\alpha-2}$ so that the signal to noise is $\propto E^{\alpha-1}$ which decreases with energy for $\alpha < 1$.

In ref. [22] a simple situation where the UHECR sky is modelled as a superposition of an isotropic component and a single nearby source has been analysed semi-analytically and fitted to the observed dipole. The contribution of the one discrete source to the total flux is parametrised by η and the deflection spread by the concentration parameter κ. Measurement of the dipole and quadrupole can fix both parameters, for example the ratio of the quadrupole to the dipole moment, C_2/C_1 fixes κ. The best fit parameters are then $\eta \simeq 0.035$ and $\kappa \simeq 2.5$, corresponding to an angular spread of the discrete source of $\simeq 50°$. These fits can be translated into constraints on source distance, luminosity and extragalactic magnetic field strength. For Centaurus A and the Virgo cluster one gets an r.m.s. field strength $B_{\rm rms} \sim 1(100\,{\rm kpc}/l_c)^{1/2}\,{\rm nG}$ for an iron dominated composition and $B_{\rm rms} \sim 10(100\,{\rm kpc}/l_c)^{1/2}\,{\rm nG}$ for a proton dominated composition, in terms of the magnetic field coherence length l_c.

The challenge is now to build astrophysical models for suitable classes of sources and for their spatial distribution, as well as for intervening magnetic fields, that are consistent with all the theoretical aspects discussed above. At the same time such models have to reproduce significant dipolar anisotropies around 8×10^{18} eV but less significant dipoles at other energies, and no significant higher multipoles at the current amount of experimental exposure. They also have to be consistent with the observed spectra and composition. So far this has not been convincingly solved. While satisfactory scenarios exist for spectrum and composition [23, 24], see also the recent review ref. [25], attempting to reproduce anisotropies at the same time is more difficult. First attempts taking into have been performed, e.g., in refs. [26, 27, 28, 29, 30, 31]. These studies suggest that the amplitude of anisotropies may be dominated by the source distribution and the most nearby sources. Magnetic fields may shift directions and mix dipoles and low order multipoles, and disentangling both influences will be a challenge.

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REFERENCES

[1] A. Aab *et al.* [Pierre Auger Collaboration], Science **357** (2017) no.6537, 1266 doi:10.1126/science.aan4338 [arXiv:1709.07321 [astro-ph.HE]].
[2] R. Jansson and G. R. Farrar, Astrophys. J. **757** (2012) 14 doi:10.1088/0004-637X/757/1/14 [arXiv:1204.3662 [astro-ph.GA]].
[3] P. Abreu *et al.* [Pierre Auger Collaboration], Astrophys. J. **762** (2012) L13 doi:10.1088/2041-8205/762/1/L13 [arXiv:1212.3083 [astro-ph.HE]].

[4] A. Aab *et al.* [Pierre Auger Collaboration], Astrophys. J. **868** (2018) no.1, 4 doi:10.3847/1538-4357/aae689 [arXiv:1808.03579 [astro-ph.HE]].

[5] A. Aab *et al.* [Pierre Auger Collaboration], Astrophys. J. **853** (2018) no.2, L29 doi:10.3847/2041-8213/aaa66d [arXiv:1801.06160 [astro-ph.HE]].

[6] A. Aab *et al.* [Pierre Auger Collaboration], JCAP **1706** (2017) no.06, 026 doi:10.1088/1475-7516/2017/06/026 [arXiv:1611.06812 [astro-ph.HE]].

[7] A. Aab *et al.* [Pierre Auger Collaboration], Astrophys. J. **804** (2015) no.1, 15 doi:10.1088/0004-637X/804/1/15 [arXiv:1411.6111 [astro-ph.HE]].

[8] R. U. Abbasi *et al.* [Telescope Array Collaboration], Astrophys. J. **862** (2018) no.2, 91 doi:10.3847/1538-4357/aac9c8 [arXiv:1802.05003 [astro-ph.HE]].

[9] A. Aab *et al.* [Telescope Array and Pierre Auger Collaborations], Astrophys. J. **794** (2014) no.2, 172 doi:10.1088/0004-637X/794/2/172 [arXiv:1409.3128 [astro-ph.HE]].

[10] O. Deligny in R. U. Abbasi *et al.* [Telescope Array and Pierre Auger Collaborations], arXiv:1511.02103 [astro-ph.HE].

[11] O. Deligny, Astropart. Phys. **104** (2019) 13 doi:10.1016/j.astropartphys.2018.08.005 [arXiv:1808.03940 [astro-ph.HE]].

[12] R. Aloisio and V. Berezinsky, Astrophys. J. **612** (2004) 900 doi:10.1086/421869 [astro-ph/0403095].

[13] M. Kachelriess and P. D. Serpico, Phys. Lett. B **640** (2006) 225 doi:10.1016/j.physletb.2006.08.006 [astro-ph/0605462].

[14] P. Abreu *et al.* [Pierre Auger Collaboration], JCAP **1305** (2013) no.05, 009 doi:10.1088/1475-7516/2013/05/009 [arXiv:1305.1576 [astro-ph.HE]].

[15] R. Alves Batista *et al.*, Front. Astron. Space Sci. **6** (2019) 23 doi:10.3389/fspas.2019.00023 [arXiv:1903.06714 [astro-ph.HE]].

[16] M. Lemoine and E. Waxman, JCAP **0911** (2009) 009 doi:10.1088/1475-7516/2009/11/009 [arXiv:0907.1354 [astro-ph.HE]].

[17] R. Y. Liu, A. M. Taylor, M. Lemoine, X. Y. Wang and E. Waxman, Astrophys. J. **776** (2013) 88 doi:10.1088/0004-637X/776/2/88 [arXiv:1308.5699 [astro-ph.HE]].

[18] A. Aab *et al.* [Pierre Auger Collaboration], Phys. Lett. B **762** (2016) 288 doi:10.1016/j.physletb.2016.09.039 [arXiv:1609.08567 [astro-ph.HE]].

[19] A. Aab *et al.* [Pierre Auger Collaboration], Phys. Rev. D **96** (2017) no.12, 122003 doi:10.1103/PhysRevD.96.122003 [arXiv:1710.07249 [astro-ph.HE]].

[20] D. Harari, S. Mollerach and E. Roulet, Phys. Rev. D **92** (2015) no.6, 063014 doi:10.1103/PhysRevD.92.063014 [arXiv:1507.06585 [astro-ph.HE]].

[21] S. Mollerach and E. Roulet, Phys. Rev. D **99** (2019) no.10, 103010 doi:10.1103/PhysRevD.99.103010 [arXiv:1903.05722 [astro-ph.HE]].

[22] A. Dundović and G. Sigl, JCAP **1901** (2019) no.01, 018 doi:10.1088/1475-7516/2019/01/018 [arXiv:1710.05517 [astro-ph.HE]].

[23] M. Kachelrieß, O. Kalashev, S. Ostapchenko and D. V. Semikoz, Phys. Rev. D **96** (2017) no.8, 083006 doi:10.1103/PhysRevD.96.083006 [arXiv:1704.06893 [astro-ph.HE]].

[24] M. S. Muzio, M. Unger and G. R. Farrar, arXiv:1906.06233 [astro-ph.HE].

[25] M. Kachelriess and D. V. Semikoz, arXiv:1904.08160 [astro-ph.HE].

[26] G. Sigl, F. Miniati and T. A. Ensslin, Phys. Rev. D **70** (2004) 043007 doi:10.1103/PhysRevD.70.043007 [astro-ph/0401084].

[27] S. Hackstein, F. Vazza, M. Brüggen, G. Sigl and A. Dundovic, Mon. Not. Roy. Astron. Soc. **462** (2016) no.4, 3660 doi:10.1093/mnras/stw1903 [arXiv:1607.08872 [astro-ph.CO]].

[28] B. Eichmann, J. P. Rachen, L. Merten, A. van Vliet and J. Becker Tjus, JCAP **1802** (2018) no.02, 036 doi:10.1088/1475-7516/2018/02/036 [arXiv:1701.06792 [astro-ph.HE]].

[29] S. Hackstein, F. Vazza, M. Brüggen, J. G. Sorce and S. Gottlöber, Mon. Not. Roy. Astron. Soc. **475** (2018) no.2, 2519 doi:10.1093/mnras/stx3354 [arXiv:1710.01353 [astro-ph.CO]].

[30] D. Wittkowski and K. H. Kampert, Astrophys. J. **854** (2018) no.1, L3 doi:10.3847/2041-8213/aaa2f9 [arXiv:1710.05617 [astro-ph.HE]].

[31] O. Kalashev, M. Pshirkov and M. Zotov, arXiv:1810.02284 [astro-ph.HE].