Anisotropies of ultra-high energy cosmic rays

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We summarize the types of anisotropy expected in the arrival directions of ultra-high cosmic rays (UHECRs) of extragalactic origin in several energy regimes. We also briefly discuss the information on UHECRs encoded in these patterns which may be extracted by forthcoming experiments.

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Introduction. The origin of cosmic rays is still partially unknown, despite the fact that one century has passed since the discovery of their extraterrestrial nature by Hess. The main problem resides in the fact that they are charged particles: the directional information is lost by repeated scattering in interstellar magnetic fields, thus preventing the direct identification of the sources. Above $\sim 10^{18} - 10^{19}$ eV (ultra-high energy cosmic rays, UHECRs) the rigidity of cosmic rays of galactic origin is high enough that the deflection in the galactic magnetic field (GMF) should not completely wash out correlations between their arrival directions and the galactic plane. The lack of any correlation down to the percent level and the difficulty to find suitable galactic candidates for acceleration up to 2–3$\times 10^{20}$ eV suggest an extragalactic origin for UHECRs. This hypothesis immediately raises the possibility that UHECRs may be messengers from deep space, and thus potential cosmic tracers of structures. Vice versa, one may exploit the present knowledge of the universe to infer some information on UHECR properties. In the following we summarize what can be learnt on UHECRs from the expected anisotropies in their arrival directions. For the sake of simplicity, we shall limit ourselves to "astrophysical" scenarios for UHECR acceleration, although interesting and often distinctive directional signatures arise also in exotic models for UHECR production.[1]

UHECR anisotropy at large scales. The anisotropies expected for extragalactic cosmic rays can be classified into:

i) Small scale clustering.
ii) Anisotropies on medium-large scales.

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iii) Proper motion dipole (Compton-Getting effect).
iv) Rigidity effect due to the GMF.

i) At energies high enough that deflections in extragalactic and galactic magnetic fields are sufficiently small, point sources may reveal themselves as small-scale clusters of UHECR arrival directions. This requires additionally a rather low density of UHECR sources so that the probability to observe several events of at least a subset of especially bright sources is large enough. We shall not review here the numerous studies that have been performed on this scenario especially after the AGASA claim of a statistically significant clustering of events;[2] unfortunately, other experiments with comparable or larger statistics have not yet confirmed this claim.[3,4]

ii) Moving to lower energies, the energy-loss horizon of UHECRs and thereby the number of visible sources increases. Also, the number of potential accelerators should increase. Finally, deflections in magnetic fields become more important. As a result, the identification of single sources is challenging if not impossible. However, if UHECR sources trace to some degree the inhomogeneous distribution of matter revealed by the observed large scale structure (LSS) surveys within a few hundreds Mpc, some anisotropies on medium-large scales should be detectable. In[5] it was evaluated the expected anisotropy in the UHECR arrival distribution starting from the IRAS PSCz astronomical catalogue of nearby galaxies, taking into account the main selection effects in the catalogue as well as UHECR propagation effects. The conclusion was that to confirm this scenario one needs about $300 - 400$ events at $E \gtrsim 4 - 5 \times 10^{19}$ eV, which should be attained by the Auger experiment within a decade or so. Yet, by combining the $\mathcal{O}(100)$ events at $E \gtrsim 4 - 5 \times 10^{19}$ eV already collected by the previous generation of instruments, the authors of[6] found some evidence of a broad maximum of the cumulative two-point autocorrelation function of UHECR arrival directions around 25 degrees. The authors suggested that, given the energy dependence of the signal and its angular scale, it might be interpreted as a first signature of the large-scale structure of UHECR sources and of intervening magnetic fields. Recently, this claim was analyzed on the basis of sky maps derived from the PSCz catalogue.[7] It was found that the above mentioned result is indeed inconsistent with a purely isotropic sky, but consistent within 2 σ with the expectations for UHECRs tracing the LSS. A more-than-linear bias with overdensity improves the agreement. The still low statistics and the role of the magnetic field deflections may explain why no significant *cross-correlation* between data and LSS overdensities is found.

iii) At even lower energies, also the LSS structure of sources disappears, both because the inhomogeneities in the source distribution will be averaged out due to the increased energy-loss horizon of UHECRs and because of deflections in the extragalactic magnetic fields. Thus, if the Earth were in the cosmological rest frame the CR sky would appear isotropic. The observation of the cosmic microwave background (CMB) dipole clearly shows that this is not the case, and a dipole anisotropy of 0.6% in the cosmic ray intensity is expected if the CR flux is dominated by sources

at cosmological distance. The shift of the dipole as function of energy provides information about the mean charge of CRs and the GMF. A 3 σ detection of this effect requires around 10^6 events in the considered energy range and is thus challenging but not impossible with present detectors, at least at energies below 10^{19} eV. A similar effect also allows one to constrain the fraction of the diffuse gamma-ray background emitted by sources at cosmological distance, with promising detection possibilities for the GLAST satellite.[8]

iv) Finally, if the extragalactic flux is still the dominant component at sufficiently low energy, the GMF may introduce blind regions on the external sky, which translate into observable anisotropies for an Earth-based observer, even if the UHECR flux is isotropic at the boundary of the Milky Way. Although the details depend on the GMF model, anisotropies of this kind should be expected in scenarios invoking a dominant extragalactic proton component already at $E \sim 4 \times 10^{17}$ eV or extragalactic iron nuclei at $E < 10^{19}$ eV.[9]

Conclusions. Anisotropies are an important tool to distinguish between different origin and primary models for the UHECRs, nicely complementing the information on the energy spectrum and chemical composition. We have briefly summarized several signatures which one expects to show up in the pattern of UHECR arrival directions at different energies. Unfortunately, the numerous unknowns make it impossible at present to determine precisely the exact energy ranges where the above-mentioned regimes are realized in nature, although theoretical expectations put this window at $10^{18} - 10^{20}$ eV. Experiments like Auger and Telescope Array have realistic chances to detect these features, which would ultimately allow astronomers to acquire new and "ultra-energetic" tools to explore the cosmos.

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