Anisotropies and clustering of extragalactic cosmic rays

M. Kachelrieß

Institutt for fysikk, NTNU, N–7491 Trondheim, Norway

Deviations from isotropy have been a key tool to identify the sources and the primary type of cosmic rays (CRs) at low energies. We argue that anisotropies due to blind regions induced by the Galactic magnetic field, the cosmological Compton-Getting effect, medium-scale anisotropies reflecting the large-scale distribution of CR sources and the small-scale clustering of the CR arrival directions at the highest energies may play the same role for extragalactic CRs.

1. Introduction

Ultrahigh energy cosmic ray (UHECR) physics has gained increasing momentum both on the experimental and the theoretical side [1]. In the latter area, the attention has shifted from ideas involving new physics as explanation for the AGASA excess to the study of signatures of extragalactic cosmic rays and attempts to identify their sources. An important example of this development is the reinterpretation of the ankle as dip produced by $e^+e^−$ pair production of extragalactic UHE protons on CMB photons suggested in Ref. [2]. As a consequence, the transition from Galactic to extragalactic CRs should occur at much lower energies than previously thought, offering experiments the possibility to study CRs from cosmological distances with high statistics.

The results of the two experiments with the largest exposure until 2005, the ground-array AGASA and the fluorescence experiment HiRes, point in several respects (GZK suppression, small-scale clusters, correlations, anisotropy towards the Galactic center) into different directions [3]. These discrepancies are in most cases statistically not very significant because of the relatively small number of events, but they obstruct a consistent interpretation of the data. While the present state of observations is thus still puzzling, new experiments like the Pierre Auger Observatory (PAO) [4], the Telescope Array (TA) [5] and the JEM-EUSO project [6] are expected to shed light on some of the unresolved issues with their improved detection techniques and increased statistics.

Reducing experimental uncertainties and increasing the number of observed events is obviously a pre-requisite to unravel the conundrum of UHECRs. However, for many questions the use of the optimal tools to analyze the data may be crucial. An example is the transition between galactic and extragalactic CRs that is usually searched for by studying the chemical composition of CRs. Here, one assumes that the end of the galactic CR spectrum is heavy (motivated by confinement and acceleration arguments) and that the extragalactic component is light. At present, uncertainties in the hadronic interaction models obstruct a reliable differentiation even between the extreme cases of proton and iron primaries at energies of $10^{18}$ eV and higher, as it is witnessed by the differing conclusions in Ref. [7]. Even worse, this method fails completely if the extragalactic component is also dominated by heavy nuclei.

A complementary tool to study the transition from galactic to extragalactic cosmic rays is the cosmological Compton-Getting effect (CCG) suggested recently in Ref. [8]. This anisotropy is not only a signature for CRs originating from cosmological distances but can serve also a tool to determine the mean charge of UHECRs primaries and the galactic magnetic field, as will be discussed in Sec. 3 of this short review.

The CCG effect requires that inhomogeneities in the source distribution of CRs are averaged out. As the free mean path of CRs decreases
for increasing energy, anisotropies connected to the large-scale structure (LSS) of CR sources should become more prominent and replace the CCG. Reference 9 analyzed the available data set of CR arrival directions and found evidence for anisotropies on the scale of 30 degrees, consistent with the theoretical expectations for anisotropies associated with the LSS from Ref. 10. These results are discussed in Sec. 4.

Finally, at sufficiently high energies deflections in magnetic fields become negligible and a small number of bright point sources results in small-scale clusters of arrival directions around or near the true source positions. Accumulating enough events, the identification of sources will become possible using e.g. correlation studies. Various studies have been pursued in this direction 11,12,13,14,15,16,17,18,19,20 and are briefly reviewed in Sec. 5. We start this short review of possible anisotropies of extragalactic CRs with a discussion of the role of galactic and extragalactic magnetic fields in the next section.

2. The role of galactic and extragalactic magnetic fields

The galactic magnetic field (GMF) consists of a regular and a stochastic component. The latter averages out along the trajectory of a CR and affects the arrival direction of most CRs only mildly. Also the impact of magnetic lensing 21 is alleviated by the energy dependent magnification and position of caustics, if an event sample cannot be binned sufficiently fine in energy.

A generalized version of the Liouville theorem for CRs propagating in magnetic fields ensures the constancy of the phase space volume along the particle trajectories: When the density of CR trajectories is increased by the GMF, the angular spread of their velocities increases also, so that the CRs arrive from a larger solid angle. Both effects compensate each other in the flux per unit solid angle, and as a consequence an isotropic flux remains isotropic to an observer behind a magnetized environment. However, the GMF introduces anisotropies for an isotropic flux outside the Galaxy, if blind regions on the external sky exist for an observer.

A simple analytic estimate of this effect can be given e.g. for a dipole field 22. Because of the azimuthal symmetry, the Størmer theory can be applied to determine the rigidity cutoff $R_S$ below which no particle can reach the Earth from a certain direction. Since the Earth is at zero galacto-magnetic latitude, one obtains $R_S = (\epsilon \mu G)/(2R^2_G)$, with $\epsilon \leq 1$ depending on the arrival direction of the CR. If the tiny vertical component detected at the solar system of $0.2 \mu G$ is due to a dipole field, then $\mu G \simeq 120 \mu G$ and $R_S$ varies in the range $10^{17} \text{V} - 10^{18} \text{V}$. Although the geometry of the GMF is more complicated than a simple dipole, one expects qualitatively similar results for more realistic models of the GMF. Comparing the Larmor radius to the thickness of the Galactic magnetic disk, $\mathcal{O}(100 \text{pc})$, shows that for $B \simeq \text{few } \mu G$ particles with $R \lesssim 10^{17} \text{V}$ are likely to be trapped. Numerical calculations confirm this estimate 22, although precise quantitative statements depend on the GMF considered. Note that the argument can be turned around: For a given rigidity cutoff $R_S$, large-scale anisotropies should be seen around $E \sim Z e R_S$, if an extragalactic component dominates at this energy. Thus, models that invoke a dominating extragalactic proton component already at $E \simeq 4 \times 10^{17} \text{eV}$ or extragalactic iron nuclei at $E \lesssim 10^{19} \text{eV}$ might be inconsistent with the observed isotropy of the CR flux.

Searches for point sources of charged CRs are affected by deflections in the GMF. Figure 1 shows a deflection map from Ref. 22 for a specific GMF model presented in 23 and a rigidity of $4 \times 10^{19} \text{V}$. The map refers to the direction as observed at the Earth and uses a Hammer-Aitoff projection of galactic coordinates. The expected deflections depend strongly on the direction, but typically trajectories passing the Galactic center or plane suffer larger deflections. Moreover, the magnitude as well as the direction of the deflections depend on the GMF model considered. Thus an experiment on the southern hemisphere like the PAO might optimize searches for point sources by cutting out part of its field of view—or might try to correct for deflections in the GMF and thereby test specific models for the GMF.

The trajectory of a charged CR in the extra-
galactic magnetic field (EGMF) has the character of a random walk, each step approximately an arc of curvature radius equal to the Larmor radius and size equal to the correlation length $L_c$ of the corresponding patch of the EGMF. Therefore the average deflection is zero and the root-mean-square deflection $\delta_{\text{rms}}$ is

$$\delta_{\text{rms}} \approx 0.2^\circ \frac{4 \times 10^{19} \text{eV}}{E} \frac{Z B_{\text{rms}}}{10^{-11} \text{G}} \frac{L}{\text{Gpc}} \frac{L_c}{\text{Mpc}}^{1/2}.$$  

For a calculation of $\delta_{\text{rms}}$ one needs either observational data or theoretical predictions both for the magnitude and the structure of EGMFs. Observational evidence for EGMFs has been found only in a few galaxy clusters observing their synchrotron radiation halos or performing Faraday rotation measurements. The two methods give somewhat different results for the field strength in clusters, with $B \sim 0.1–1 \mu \text{G}$ and $B \sim 1–10 \mu \text{G}$, respectively. Outside of clusters only upper limits exist for the EGMF.

A successful predictions of EGMFs requires a convincing theory for its origin and its amplification mechanism, but such a theory has not emerged yet. The seed fields of EGMF could be created in the early universe, e.g. during phase transitions, and then amplified by MHD processes. Alternatively, an early population of starburst galaxies or AGN could have generated the seeds of the EGMFs at redshift between five and six, before galaxy clusters formed as gravitationally bound systems. In both cases, a large fraction of the universe may be filled with seed fields for EGMFs. A quite different possibility is that the ejecta of AGN magnetized the intracluster medium only at low redshifts, and that thus the EGMF are confined within galaxy clusters and groups. Other mechanisms have been suggested and hence no unique model with unique predictions for the EGMF exists.

In the last few years, magnetic fields have been included in simulations of large scale structures [24, 25, 26]. These simulations differ both in the input physics (seed fields, amplification mechanism), the numerical algorithms and the extraction of the results. Therefore, it should be not too surprising that their result disagree strongly: While charged particle astronomy may not be possible according to Ref. [24], the deflections found in Ref. [25] are small in a large part of the sky.

Instead of viewing the results of these simulations as predictions for the EGMF, it is more appropriate to see them as tests if the used origin of the seeds field and amplification mechanism can reproduce the observational data. It is more likely that future UHECR data might teach us something about the EGMF and its origin than vice versa. Another way to detect in particular extremely small magnetic fields in voids is the search of extended TeV gamma-ray sources suggested in Ref. [27].

3. Cosmological Compton-Getting effect

Compton and Getting first discussed that a relative motion of observer and CR source results in an anisotropic CR flux, using this effect as signature for the Galactic origin of CRs with $E \gtrsim 0.1 \text{GeV}$. Similarly, the movement of the Sun relative to the microwave background frame in-
duces a dipole anisotropy in any diffuse cosmic flux.

Lorentz invariance requires that the phase space distribution function \( f \) in the frame of the observer, \( f'(r', p') \), equals the one in the frame in which the UHECR flux is isotropic, \( f(r, p) \). Expanding in the small parameter \( p - p' \approx -p \mathbf{u} \), it follows

\[
f'(p') = f(p') - p \mathbf{u} \frac{\partial f(p')}{\partial p'} + \mathcal{O}(u^2)
\]

\[
= f(p') \left( 1 - \frac{u \cdot p}{p} \frac{d \ln f}{d \ln p'} \right).
\]

Since \( u \equiv |\mathbf{u}| \ll 1 \), the anisotropy induced by the CCG effect is dominated by the lowest moment, i.e. its dipole moment. Changing to the differential intensity \( I(E) \approx p^2 f(p) \), one obtains

\[
I'(E') \approx I(E) \left[ 1 + \left( 2 - \frac{d \ln I}{d \ln E'} \right) \frac{u \cdot p}{p} \right].
\]

Thus the dipole anisotropy due to the CCG effect has the amplitude

\[
A_{\text{CCG}} = \frac{I_{\text{max}} - I_{\text{min}}}{I_{\text{max}} + I_{\text{min}}} = \left( 2 - \frac{d \ln I}{d \ln E} \right) u.
\]

Taking into account the observed spectrum \( I(E) \propto E^{-2.7} \) of cosmic rays above the ankle, \( A_{\text{CCG}} = (2 + 2.7) u \approx 0.6\% \). The annual motion of the Earth induces only an additional subleading (8%) modulation in the vector \( u \).

Theoretical predictions of anisotropies for galactic sources depend on the GMF and the exact source distribution: The amplitude \( A \) of galactic anisotropies increases with energy and may range from \( A \sim 10^{-4} \) at \( E \sim 10^{14} \) eV to \( A \sim 10^{-2} \) at \( E \sim 10^{17} \) eV [28].

The flux of extragalactic UHECRs is isotropic in the rest frame of the CMB at energies \( E \gtrsim E_s \), for which the energy-loss horizon \( \lambda_{\text{hor}} \) of CRs is large compared to the scale of inhomogeneities in their source distribution. In the same energy range, peculiar velocities average out on cosmological scales and the UHECR flux is thus isotropic at leading order. The exact value of \( E_s \) depends both on the density of the CR sources and on the primary type, but \( E_s \lesssim 4 \times 10^{19} \) eV is a conservative estimate: For protons \( \lambda_{\text{hor}} \) is at the Gpc scale at \( E \lesssim 10^{19} \) eV, decreasing to about 600 Mpc at \( 4 \times 10^{19} \) eV due to the onset of the pion production on the CMB, and rapidly dropping to few tens of Mpc at larger energies. For iron nuclei, \( \lambda_{\text{hor}} \) abruptly drops below the Gpc scale only at \( E \sim 10^{20} \) eV when photo-dissociation processes on the microwave and infrared backgrounds are possible. For typical UHECRs source densities of \( n_s = \text{few} \times 10^{-5} \text{Mpc}^{-3} \) [15,29], the number \( N_s \) of sources contributing to the observed flux can be estimated neglecting cosmological effects as

\[
N_s \sim \frac{4\pi}{3} \lambda_{\text{hor}}^3 n_s \sim 4 \times 10^4 \frac{n_s}{10^{-5} \text{Mpc}^{-3}} \left( \frac{\lambda_{\text{hor}}}{\text{Gpc}} \right)^3.
\]

Since Poisson fluctuations in \( N_s \) are roughly at the 0.5% level, one might wonder if the CCG effect could be mimicked by a fluctuation in the number of source per hemisphere. However, as long as EGMFs wash-out anisotropies, the dominant intrinsic fluctuation is due to the number of events \( N_o \) observed at the Earth and not to \( N_s \), even for relatively low \( N_s \). Observational tests that \( E_s \) was chosen low enough are: (i) the approximate alignment of the dipole axis of \( A_{\text{CCG}} \) with the one in the CMB; (ii) the absence of higher multipole moments in the observed maps: While fluctuations in the number of cosmological sources should lead to higher multipole modes \( l > 1 \) with similar intensity \( A^{(l)} \), they are suppressed by powers of \( u \) in the case of the CCG effect, \( A^{(l)} \propto u^l \).

The signatures and the properties of the CCG effect are:

(i) The amplitude \( A_{\text{CCG}} \) of the anisotropy is charge- and energy-independent, as long as the UHECR flux in the energy range studied is dominated by sources at cosmological distance.

(ii) Since the CCG effect is a dipole anisotropy, the magnitude of its amplitude should be robust against deflections of UHECRs in the GMF, and only the dipole axis is displaced. For instance, at energies \( 2-3 \times 10^{19} \) eV and for proton primaries, the dipole position should be aligned to the one observed in the CMB within about 10°.

(iii) Observing the CCG feature at only one energy provides combined information on the intervening GMF and the charge of the cosmic ray...
primaries. However, observations at two or more energies break this degeneracy. For example, the determination of the average primary charge is straightforward as long as CRs propagate in the quasi-ballistic regime and given by the ratio of the shifts of the CR and CMB dipole axis at two different energies.

(iv) Moving to lower energies, the anisotropy due to the CCG effect should disappear as soon as galactic CRs start to dominate. Relatively large anisotropies connected to an increased source density in the disc or towards the galactic center are expected to turn on somewhere between $10^{17}$ eV and the ankle. Alternatively, blind regions may induce anisotropies in the extragalactic CR flux at low energies, as discussed in Sec. 2.

(v) Moving to sufficiently high energies, $\lambda_{\text{hor}}$ decreases and anisotropies due to local inhomogeneities in the distribution of sources are expected to dominate. This effect will be discussed in more detail in the next Section.

Is it possible for present experiments to detect a 0.6% dipolar anisotropy in the UHECR flux? In a sample of $N$ events, typical fluctuations are of the order of $\sqrt{N}$. Thus a 0.6% level sensitivity is only reached for $\sqrt{N}/N \approx 0.006$ or $N \approx 3 \times 10^4$ events. Reference [30] gave an empirical fit for the expected error $\sigma_A$ in the determination of the amplitude of a dipole anisotropy as function of the event number $N$ and the declination $\delta$ of the dipole vector, $\sigma_A = \sqrt{3/N} \left(1 + 0.6 \sin^3 \delta \right)$, where a detector located at the PAO site and a maximum zenith angle of $60^\circ$ were assumed. This implies that a $3\sigma$ detection of a 0.6% anisotropy requires of the order of $10^6$ events and it thus unlikely for the PAO. Since the UHECR spectrum is steep, better detection possibilities are at lower energies, say at $10^{18}$ eV or below, which will be explored in the near future by the PAO and especially the TA. A negative result would question a transition from galactic to extragalactic cosmic rays close or below the energy range considered.

4. Medium-scale clustering

The CCG effect requires that inhomogeneities in the source distribution of CRs are averaged out. As the free mean path of CRs decreases for increasing energy, anisotropies connected to the large-scale structure (LSS) of CR sources become more prominent and replace the CCG. The exact value of this transition energy $E_*$ depends both on the amount of clustering in the source distribution and the free mean path $\lambda_{\text{CR}}$ of CRs, i.e. also the primary type. For the specific case of proton primaries and a source distribution proportional to the density of baryons, Ref. [14] found $E_* \approx 5 \times 10^{19}$ eV and a minimal number of events of order 100 for a detection.

The available data set of UHECR events with published arrival directions consists of the SUGAR data with energy above $E \geq 1 \times 10^{19}$ eV [31], the Yakutsk data as presented at the ICRC 2005 [32], the AGASA data set until May 2000 from Ref. [33], and the HiRes stereo data set [34,35]. Additionally, the arrival directions of six events from Haverah Park, Volcano Ranch and Flye’s Eye with $E > 10^{20}$ eV are given in Ref. [1].

This data set consists of $O(100)$ events and may be already used to test medium-scale clustering. In this section we review the results of such a test performed in Ref. [9].

Since the absolute energy scale of each experiment has a rather large uncertainty, the energies $E$ given by the experiments have to be shifted to new energies $E'$ to reproduce correctly spectral features like e.g. the dip. A crucial ingredient of any analysis that combines data of several experiments and depends on the correct (relative) assignment of event energies is therefore their consistent rescaling.

In Ref. [9], the energy rescaling was performed following Refs. [32,37], but using for convenience the HiRes energies as reference energy $E'$. The angular two-point auto-correlation function $w$ in its cumulative version was used as statistical estimator for possible deviations from an isotropic distribution of arrival directions. Thus $w$ as function of the angular scale $\delta$ was defined as

$$w(\delta) = \sum_{i=1}^{N} \sum_{j=1}^{i-1} \Theta(\delta - \delta_{ij}),$$

where $\Theta$ is the step function, $N$ the number of CRs considered and $\delta_{ij}$ the angular distance between the two cosmic rays $i$ and $j$. Having
performed a large sample of Monte Carlo simulations, the (formal) chance probability $P(\delta)$ to observe a larger value of the autocorrelation function $w(\delta)$ is the fraction of simulations with $w > w^*$, where $w^*$ is the observed value. Since the search and cut criteria were not fixed a priori, the probabilities obtained in Ref. [9] are only indicative. But they can be used in particular to compare for different data sets the relative likelihood to observe the signal as chance fluctuation.

Figure 2 shows the chance probability $P(\delta)$ as function of the angular scale $\delta$ for different combinations of experimental data. The chance probability $P(\delta)$ shows already a $2\sigma$ minimum around $20–30$ degrees using only the 27 events of the HiRes experiments with $E' \geq 4 \times 10^{19}$ eV. Adding more data, the signal around $\delta = 25^\circ$ becomes stronger, increasing from $\sim 2\sigma$ for 27 events to $\sim 3.5\sigma$ for 107 events. The position of the minimum of $P(\delta)$ is quite stable adding more data and every additional experimental dataset contributes to the signal. Moreover, autocorrelations at scales smaller than $25^\circ$ become more significant increasing the dataset.

To understand better how the search at arbitrary angular scales influences the significance of the signal, Ref. [9] calculated the penalty factor for the scan of $P(\delta)$ over $\delta$. The penalty factor increases for increasing resolution $\Delta\delta$ of the angular scale $\delta$, but reaches an asymptotic value for $\Delta\delta \to 0$. The numerical value of the penalty factor found in the limit $\Delta\delta \to 0$ varies between 6 for the HiRes data set alone and 30 for the combination of all data. Since the energy cut was determined by the one chosen in Ref. [35], no additional penalty factor for the energy had to be included. Thus the true probability to observe a larger autocorrelation signal by chance is $P \approx 3 \times 10^{-3}$ for the complete data set.

The addition of data with energy below $E' \approx 4 \times 10^{19}$ eV reduces the significance of the minimum of $P(\delta)$, cf. Fig. 3. For this check one can use only Hires and SUGAR data, since for the other experiments no arrival directions for events below $E' = 4 \times 10^{19}$ eV are published. Moreover, the energy bin size was dictated by the one chosen in Ref. [35].

The reduction of the minimum of $P(\delta)$ could have various reasons: First, the interaction length of the UHECR primaries can increase with decreasing energy, as in the case of protons or nuclei. Then, the projection on the two-dimensional
skymap averages out more and more three-dimensional structures. Second, deflections in the Galactic and extragalactic magnetic fields destroy for lower energies more and more correlations. Note that the autocorrelation signal would not disappear lowering the energy threshold, if it would be caused solely by an incorrect combination of the exposure of different experiments.

These results, if confirmed by future independent data sets, have several important consequences.

Firstly, anisotropies on intermediate angular scales constrain the chemical composition of UHECRs. Iron nuclei propagate in the Galactic magnetic field in a quasi-diffusive regime at $E = 4 \times 10^{19}$ eV and correlations would be smeared out on scales of $\sim 30^\circ$. Therefore, models with a dominating extragalactic iron component at the highest energies are disfavored by anisotropies on intermediate angular scales. Since the relative deflections of CRs in the same energy range is reduced, a conclusive statement requires however a larger event sample.

Secondly, the probability that small-scale clusters are indeed from point sources will be reduced if the clusters are in regions with an higher UHECR flux. By contrast, the observation of clusters in the "voids" would be less likely by chance than in the case of an UHECR flux without medium scale anisotropies.

However, the most important consequence of these findings is the prediction that astronomy with UHECRs is possible at the highest energies. The minimal energy required seems to be around $E' = 4 \times 10^{19}$ eV, because at lower energies UHECR arrive more and more isotropically. This trend is expected, because at lower energies both deflections in magnetic fields and the average distance $l$ from which UHECRs can arrive increase. Since the two-dimensional skymap corresponds to averaging all three-dimensional structures (with typical scale $L$) over the distance $l$, no anisotropies apart from the CCG effect are expected for $l \gg L$. Thus, if the signal found in Ref. [9] will be confirmed it has to be related to the local large scale structure.

5. Small-scale clustering

The presence of small-scale cluster, i.e. cluster of events within the angular resolution of UHECR experiments, was first noticed for the AGASA data in Ref. [11]. About 20% of the world data set with energy $\geq 4 \times 10^{19}$ eV measured at that time were clustered in angular doublets or even triplets; both triplets are found near the supergalactic plane. The chance probability to observe the clustered events in the case of an isotropic distribution of arrival directions was estimated to be $< 1\%$ [12].

In particular the AGASA data set consisting of four pairs and one triplet within 2.5° out of $N = 57$ CRs was analyzed by various groups [11, 12, 13, 14, 15]. The statistical significance ascribed to the clustering signal varies however strongly in different analyzes [11, 12, 13, 14, 15]. This variance is explained partly by the difficulty of assigning a posteriori a chance probability to a search for a signal without prescribing a priori the cuts. Moreover, the HiRes experiment [34] has not confirmed clustering yet, but this finding is still compatible with expectations [14, 15]. The preliminary data of the PAO have been searched only for single sources, with negative result [39]. From our discussion of the influence of the GMF on the arrival direction of UHECRs it is clear that the expected deflection towards the GC are larger. Moreover, they depend strongly on the size of the dipole field. It may be therefore essential for searches of point sources using the data of the PAO to apply models of the GMF and to correct for the resulting deflections.

Finally, there is the open question of correlations of UHECR arrival directions with BL Lacs, put forward first in Ref. [17]. Additionally to the first claim of proton primaries correlated with the AGASA and Yakutsk data, Ref. [19] found a correlation of a neutral component at lower energies

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1Reference [38], appearing after the workshop took place, compared the proposed signal with the clustering properties expected from the PSCz catalogue of galaxies. Its authors argued that the chance probability of the signal is consistent within 2 sigma with the expectations from the PSCz catalogue. No evidence for a significant cross-correlation of the observed events with the LSS overdensities was found, which may be explained by deflections in magnetic fields and the limited statistics.
with the HiRes data. The status of these correlations is still disputed at present; a summary of the various correlation claims and also a forecast can be found in Ref. [20].

6. Summary and conclusions

Possible anisotropies expected for extragalactic cosmic rays can be classified into four subclasses: i) At such high energies that deflections in extragalactic 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. ii) Moving to lower energies, the energy-loss horizon of UHECRs and thereby the number of sources visible increases. Moreover, deflections in magnetic fields become more important. As a result, the identification of single sources is not possible anymore. Instead, anisotropies on medium scales should reflect the inhomogeneous distribution of UHECR sources that is induced by the observed LSS structure of matter. 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 EGMF. Thus the CR sky would appear isotropic, if the Earth would be at rest with respect to the cosmological rest frame. As the observation of the CMB dipole shows, this is not case, and a dipole anisotropy of 0.6% 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. iv) Finally, the GMF can induce anisotropies in the observed flux of extragalactic UEHCRs (even if it is isotropic at the boundary of the Milkyway), for rigidities low enough that blind regions exist. According to the estimates of Ref. [22] anisotropies of this kind should be expected in models that invoke a dominating extragalactic proton component already at $E \approx 4 \times 10^{17}$ eV or extragalactic iron nuclei at $E \lesssim 10^{19}$ eV.

It is not guaranteed that all these four anisotropies can be observed. If EGMFs are large, UHECR primaries are nuclei and/or the source density is large, the integrated flux above the energy where point sources become visible may be for the present generation of UHECR experiments too small. Similarly, a transition from galactic to extragalactic sources at a relatively high energy reduces the chances to observe the CCG effect.

Experimentally, the easiest accessible anisotropy is the medium-scale anisotropy connected to the LSS of UHECR sources. Here, the event number required to confirm the proposed signal in Ref. [9] should be collected within one or two years by the PAO.

Acknowledgments

It is a pleasure to thank Dima Semikoz and Pasquale Serpico for fruitful collaborations on which this talk is based on, and to thank Dima Semikoz also for comments on this draft.

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