On the Anisotropy in the Arrival Directions of Ultra-high-energy Cosmic Rays

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Abstract

We present results of elaborate four-dimensional simulations of the propagation of ultra-high-energy cosmic rays (UHECRs), which are based on a realistic astrophysical scenario. The distribution of the arrival directions of the UHECRs is found to have a pronounced dipolar anisotropy and rather weak higher-order contributions to the angular power spectrum. This finding agrees well with the recent observation of a dipolar anisotropy for UHECRs with arrival energies above 8 EeV by the Pierre Auger Observatory and constitutes an important prediction for other energy ranges and higher-order angular contributions for which sufficient experimental data are not yet available. Since our astrophysical scenario enables simulations that are completely consistent with the available data, this scenario will be a very useful basis for related future studies.

Key words: astroparticle physics – cosmic rays – magnetic fields

1. Introduction

Although ultra-high-energy cosmic rays (UHECRs), i.e., cosmic charged nuclei with energies $\geq 1$ EeV, have been investigated for more than half a century (Linsley 1963; Nagano & Watson 2000), most of the main questions regarding UHECRs are still unanswered (see, e.g., Kotera & Olinto 2011). For example, it is not yet known from which sources UHECRs originate, what the chemical composition of the particles at their sources is, and how the particles are accelerated (Sigl 2001; Kachelriess & Serpico 2006). A way to investigate these issues is to make assumptions about the origin, source composition, etc., of UHECRs, to simulate their propagation to Earth under these assumptions, and to compare the simulation results with observational data. Typical observables for comparing the results of simulations and experiments are the energy spectrum, mass spectrum (Aab et al. 2017a), and distribution of arrival directions of UHECRs reaching the Earth. From these observables, the last one allows the most direct conclusions about the locations of the sources.

In recent years, there have been strong efforts to study the directional distribution of UHECRs arriving at Earth and observational hints for an anisotropy in the arrival directions have been reported (Abbasi et al. 2014; Aab et al. 2015; Al Samarai 2015; Aab et al. 2017b). However, a statistically significant (significance level $s > 5\sigma$) detection of a UHECR anisotropy was not possible until very recently. The Pierre Auger Collaboration reported the discovery of a significant dipolar anisotropy ($s = 5.2\sigma$) for cosmic particles arriving with energies $E > 8$ EeV (Aab et al. 2017c). This experimental work represents important progress toward the identification of the sources of UHECRs. Still, it has some observational limitations. First, it focuses on the existence of a nonzero dipole moment in the orientational distribution of the arrival directions, as the statistics of the experimental data does not allow it to significantly prove higher-order multipole moments. Second, for similar reasons, no higher arrival-energy ranges than $E > 8$ EeV are taken into account. The third limitation arises from the observation of UHECRs from only a part of the sky (Sommers 2001). By combining the data of the Pierre Auger Observatory with data from the Telescope Array, it has been possible to reach a full sky coverage for energies $E > 10$ EeV (Aab et al. 2014; Deligny 2015), but the data for this energy range did not allow one to find a significant ($s > 5\sigma$) anisotropy in the arrival directions and up to now there are no corresponding combined data for lower energies.

The goal of this Letter is to study the anisotropy in the arrival directions of UHECRs comprehensively without these observational limitations. For this purpose, we simulated the propagation of UHECRs from their assumed sources to Earth, taking into account deflections of the trajectories of charged particles in extragalactic and galactic magnetic fields, all relevant interactions with the photon background, as well as cosmological effects such as the redshift evolution of the photon background and the adiabatic expansion of the universe. These four-dimensional simulations are limited neither to a specific energy range nor to the consideration of particular multipole moments of the distribution of the arrival directions of UHECRs. To study the anisotropy in the arrival directions, we consider the associated angular power spectrum up to an order of 32 and its dependence on the arrival energies of the particles. Furthermore, the simulations correspond to a full sky coverage.

With these features, our work can provide guidance for future experimental studies. In contrast to earlier simulation work (Taylor 2014; Tinyakov & Urban 2015; Eichmann et al. 2017), our results are in excellent agreement with the energy spectrum, mass spectrum, as well as anisotropy of the current UHECR data collected by the Pierre Auger Observatory. In addition, the results lead to interesting predictions for energy ranges and multipole moments that are not yet accessible by the existing observatories.

2. Methods

Our four-dimensional simulations of the propagation of UHECRs to Earth were carried out using the Monte-Carlo code CRPropa 3 (Batista et al. 2016). These simulations take into account all three spatial degrees of freedom as well as the cosmological time-evolution of the universe. Regarding the sources, we assumed that they all have the same properties and that they are discrete objects, whose spatial distribution follows the local mass distribution of the universe. We chose their positions randomly such that the local large-scale mass structure resembles the model of Dolag et al. (2005). The
mineral source distance from the observer was 10 Mpc to avoid effects of nearby sources and the maximal redshift was $z \approx 1.3$, which is equivalent to a maximal comoving distance of 4 Gpc. For the source density, we chose $\rho \approx 10^{-4} \text{Mpc}^{-3}$, which is in accordance with known density bounds (Abreu et al. 2013).

In our simulations, the sources emitted $^{1}\text{H}$, $^{4}\text{He}$, $^{14}\text{N}$, $^{28}\text{Si}$, and $^{56}\text{Fe}$ isotropically with an energy spectrum

$$J_0(E_0) = \frac{dN_0}{dE_0} \propto \sum_{\alpha} f_\alpha E_0^{-\gamma} \begin{cases} 1, & \text{if } \frac{E_0}{Z_\alpha} < R_{\text{cut}}, \\ e^{1 - \frac{E_0}{Z_\alpha R_{\text{cut}}}}, & \text{if } \frac{E_0}{Z_\alpha} \geq R_{\text{cut}}, \end{cases}$$

where $dN_0(E_0)$ is the number of particles emitted with an energy in the interval from $E_0$ to $E_0 + dE_0$. Here, $f_\alpha$ is the fraction of particles of element $\alpha \in \{\text{H, He, N, Si, Fe}\}$ among all emitted particles with the normalization $\sum_{\alpha} f_\alpha = 1$, $\gamma$ is the so-called spectral index, $Z_\alpha$ is the atomic number of element $\alpha$, and $R_{\text{cut}}$ is a cut-off rigidity above which the particle flow at the sources is exponentially suppressed. We chose the source parameters $f_\alpha$, $\gamma$, and $R_{\text{cut}}$ as $f_\text{H} = 3.0\%$, $f_\text{He} = 2.1\%$, $f_\text{N} = 73.5\%$, $f_\text{Si} = 21.0\%$, $f_\text{Fe} = 0.4\%$, $\gamma = 1.61$, and $R_{\text{cut}} = 10^{18.88}\text{eV}$, since for these parameter values the energy spectrum and mass spectrum of the simulated UHECRs arriving at the observer are in optimal agreement with the corresponding data from the Pierre Auger Observatory (Wittkowski & Kampert 2017). To obtain good statistics, we emitted in total more than $10^9$ particles at the sources.

When simulating the propagation of UHECRs, their trajectories are influenced by interactions with the extragalactic photon background, by deflections in extragalactic and galactic magnetic fields, as well as by cosmological effects like the redshift evolution of the photon background and the adiabatic expansion of the universe. For the extragalactic background light, we used the model of Gilmore et al. (2012; the so-called “fiducial” model) as well as the photodisintegration cross sections from the TALYS code\footnote{http://www.talys.eu/documentation/} (Koning et al. 2005; Koning & Chroman 2012). Moreover, we applied the same extragalactic magnetic field model as in Section 4.2 of Batista et al. (2016) together with reflective boundary conditions (Haghighat 2016). The particles were propagated through the extragalactic magnetic field until they hit a sphere of radius 1 Mpc that was centered at Earth and captured all particles arriving with redshift $-0.025 < z < 0.025$. Next, the effect of the galactic magnetic field on the particles was calculated using the JF 2012 model of Jansson and Farrar (Jansson & Farrar 2012a, 2012b; Batista et al. 2016) for the galactic magnetic field. We checked that using a smaller sphere does not change the simulation results qualitatively and used the sphere of radius 1 Mpc for better statistics.

To study the distribution of the arrival directions, they were binned into a HEALPix grid\footnote{http://healpix.jpl.nasa.gov/} (Gorski et al. 2005) of 49,152 cells of the same solid angle. This resulted in a coarse-grained distribution $N(E, \hat{n})$ of the number of detected particles $N$ as a function of their arrival energy $E$ and arrival direction $\hat{n}$, where the unit vector $\hat{n}$ corresponds to the sign-inverted and normalized momentum vector of an arriving particle. Through the choice of 49,152 cells, the angular resolution of the coarse-grained distribution was similar to the angular resolution of the Pierre Auger Observatory (Bonifazi et al. 2009) in the relevant energy range. We expanded the rescaled particle number distribution $(N(E, \hat{n}) - \langle N(E) \rangle)/\langle N(E) \rangle$ with $\langle \cdot \rangle$ denoting an angular average, i.e., the relative fluctuations in the particle number, into spherical harmonics $Y_{lm}^m(\hat{n})$:

$$\frac{N(E, \hat{n}) - \langle N(E) \rangle}{\langle N(E) \rangle} = \sum_{l=0}^{l_{\text{max}}} \sum_{m=-l}^l a_{lm}(E) Y_{lm}^m(\hat{n}).$$

Here, $l_{\text{max}}$ is the maximal order of the expansion we were interested in and $a_{lm}(E)$ are the energy-dependent expansion coefficients. The angular power spectrum corresponding to the distribution of the arrival directions of the simulated UHECRs is then given by

$$C_l(E) = \frac{1}{2l + 1} \sum_{m=-l}^l |a_{lm}(E)|^2,$$

with $l \in \{0, \ldots, l_{\text{max}}\}$, where $C_0(E) = 0$ due to the rescaling of $N(E, \hat{n})$. Note that the coefficients $C_l(E)$ are energy-dependent and rotationally invariant. For $l \geq 1$, they describe the angular distribution of the arrival directions on solid angle scales $2\pi/\text{sr}$. The angular power spectrum is therefore a useful quantity to study the distribution of the arrival directions and to find possible anisotropies. We focus on the angular power spectrum rather than on the orientations associated with the multipoles, since the orientations depend strongly on the details of the model for the local mass distribution of the universe, whereas the angular power spectrum is a much more robust quantity.

To see which coefficients $C_l(E)$ can be measured in the near future with statistical significance $s > 5\sigma$, we determined the upper $5\sigma$ confidence bounds for isotropy. For this purpose, we estimated that in a few years about 50,000, 34,988, and 18,288
UHECR events with energies greater than 8 EeV, 10 EeV, and 15 EeV, respectively, will have been detected by UHECR observatories. Furthermore, for each of these three energy intervals we generated $10^3$ data sets of 50,000, 34,988, and 18,288 UHECR events, respectively, with random arrival directions that are uniformly distributed on the unit sphere. From these data sets, we then determined the mean values and standard deviations $\sigma$ of the coefficients $C_l$, which allowed us to calculate the upper $5\sigma$ confidence bound for isotropy.

3. Results

Figure 1 shows the angular power spectrum of the arrival directions of the simulated UHECRs up to an order of $l_{\text{max}} = 32$ for particles reaching the Earth with energies $E > 8$ EeV, $E > 10$ EeV, or $E > 15$ EeV.

Remarkably, for all three energy ranges, our results show a statistically significant ($s > 5\sigma$) dipolar anisotropy, whereas on smaller solid angle scales the distribution of the arrival directions is always compatible with an isotropic directional distribution. The significant dipolar anisotropy with no higher-order anisotropies for arrival energies $E > 8$ EeV (see Figure 1(a)) is in excellent agreement with the latest data of the Pierre Auger Observatory. In a recent study, the Pierre Auger Collaboration reported a significant ($s > 5\sigma$) dipolar anisotropy (Aab et al. 2017c), whereas an earlier study found isotropy for the higher-order multipole moments (Aab et al. 2017b). Similarily, our results for arrival energies $E > 10$ EeV (see Figure 1(b)) are well in line with Deligny (2015), which mentions indications of a dipolar anisotropy for the same energy range. This finding, however, is not statistically significant with reference to a significance level of $5\sigma$, but based on our simulation results we can expect that the dipolar anisotropy in the experimental data will become significant as soon as enough data are available. Deligny (2015) also consider higher-order contributions to the angular power spectrum up to an order of $l = 20$ and finds that they are compatible with isotropy. This is again consistent with our simulations and we predict that one will find no significant anisotropy also for even larger $l$ when they are addressed in experiments in the near future. Our results for arrival energies $E > 15$ EeV (see Figure 1(c)) are predictions that we expect to get confirmed by future experimental studies. We are not aware of any relevant studies considering the angular power spectrum of the arrival directions of UHECRs in this energy range.

For $E > 8$ EeV, $E > 10$ EeV, and $E > 15$ EeV the values of $C_l(E)$ are 3.74 · $10^{-3}$, 6.28 · $10^{-3}$, and 1.34 · $10^{-2}$, respectively. The corresponding dipole amplitudes $\frac{3}{2\pi\sigma}\sqrt{C_1(E)}$ are approximately 5.2 · $10^{-2}$, 6.7 · $10^{-2}$, and 9.8 · $10^{-2}$, respectively. Remarkably, the dipole amplitudes for $E > 8$ EeV and $E > 10$ EeV are close to the experimentally determined ones (Aab et al. 2017c; Deligny 2015). The values of $C_4(E)$ are noticeable for all investigated energy intervals, but will not be measurable with significance $s > 5\sigma$ in the next few years with the current UHECR observatories. Note that the nonzero size of the observer can lead to an artificial deflection that reduces the observed multipole moments (Dundovic & Sigl 2017). This reduction increases with $l$; it can be neglected for small $l$, but the results for large $l$ should be considered as lower limits. Nevertheless, up to $l_{\text{max}} = 32$ this effect is sufficiently small so that it cannot change any results in this article qualitatively.

An important feature of our simulation results is the fact that they are in very good agreement with the energy spectrum and mass spectrum as well as with the angular power spectrum of the corresponding experimental data that are currently available. Earlier studies have usually focused only on either the energy spectrum and mass spectrum or on anisotropies in the arrival directions of UHECRs, but did not present a consistent explanation for all three of these observables (Kotera & Olinto 2011; Takami et al. 2012; Taylor 2014; Tnyakov & Urban 2015). The few existing exceptions had difficulties simultaneously reproducing the experimental results for all observables. An example is the recently published work of Eichmann et al. (2017), which obtained a too strong anisotropy in the arrival directions. In contrast to these studies, our work is based on an astrophysical scenario that provides results on the energy spectrum, mass spectrum, and anisotropies that are completely consistent with the available experimental UHECR data and it allows to make predictions for energy ranges and contributions to the angular power spectrum for which sufficient experimental data are not yet available.

4. Conclusions

We have simulated the propagation of UHECRs from their assumed sources to Earth and investigated the distribution of their arrival directions. For this purpose, we carried out elaborate four-dimensional simulations that are based on a realistic astrophysical scenario, which assumes that the distribution of the sources follows the local large-scale mass structure described by the model of Dolag et al. (2005). The results of our simulations are in excellent agreement with the available UHECR data collected by the Pierre Auger Observatory. Regarding the distribution of the arrival directions, we found a remarkable dipolar anisotropy and rather weak higher-order multipole moments. The dipolar anisotropy is energy-dependent, but clearly pronounced for all arrival-energy ranges we considered ($E > 8$ EeV, $E > 10$ EeV, and $E > 15$ EeV).

These findings agree well with the recent observation of a significant dipolar anisotropy (Aab et al. 2017c), and no significant departure from isotropy for the higher-order multipole moments (Aab et al. 2017b), for arrival energies $E > 8$ EeV. They are also well in line with indications of a dipolar anisotropy, and higher-order contributions ($2 \leq l \leq 20$) to the angular power spectrum that are compatible with isotropy, reported for $E > 10$ EeV in a combined study of the Pierre Auger Collaboration and the Telescope Array Collaboration (Deligny 2015). For higher energies and higher-order multipole moments, there are at present no experimental findings corresponding to our results, which therefore constitute important predictions that we expect to get confirmed as soon as sufficient experimental data are available.

The excellent agreement of our simulations and related experimental data shows that the astrophysical scenario underlying our simulations is realistic and that it consistently describes the properties of the sources of UHECRs, their emission at the sources, and the propagation to Earth. This gives important hints on the still unknown real sources of UHECRs and their properties. Furthermore, with its outstanding features, this astrophysical scenario is a very useful basis for future simulation studies. One could use simulations based on this scenario, e.g., to predict the flux of photons that originate from interactions of UHECRs with the extragalactic...
background light. These photons are interesting since they provide additional information about the sources of UHECRs, but up to now it was not yet possible to detect photons with the particularly attractive energies $E > 1$ EeV. Therefore, predictions for the flux of such photons would be very useful. These predictions could be compared with the upper photon flux limits determined by the Pierre Auger Observatory (Aab et al. 2017d) and would help to design future gamma-ray detectors (Knödlseder 2016; Cyranoski 2017).

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