

Single source scenario describing the very end of the cosmic ray energy spectrum

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Abstract. The energy spectrum of cosmic rays is steeply falling with a suppression of the flux at the highest energies caused by energy losses during propagation or by reaching the maximum energy of cosmic accelerators. The energy spectrum at the highest energies is currently measured with high precision by two experiments, Telescope Array in the Northern hemisphere and the Pierre Auger Observatory in the Southern hemisphere. In this work, we study the possibility of explaining the shape of the energy spectrum above $10^{19.5}$ eV measured by the Pierre Auger Observatory with a single source. Using CRPropa 3 numerical simulations of cosmic ray propagation in the Universe we show possible features of such a single source that would be able to create a shape of the energy spectrum compatible with the measurement including limitations on the source distance, spectral index and mass composition.

1 Introduction

Ultra high energy cosmic rays (UHECRs) are currently measured by two major experiments; Telescope Array in the Northern hemisphere and the Pierre Auger Observatory in the Southern hemisphere. At the highest energies, the two experiments both measure a strong suppression of the flux (above $\approx 5 \cdot 10^{19}$ eV), nevertheless, the measured spectral index differs between these two observatories [1]. The steep suppression of the cosmic ray flux might be explained by either the GZK cutoff caused by particle interaction with mainly cosmic microwave background (CMB) or by reaching the maximum acceleration capabilities of astrophysical sources in our UHECR horizon, or a combination of both. However, a disagreement between the two observatories might be caused by the ability of the two experiments to observe different sources on the sky in the Northern and Southern hemispheres that are able to accelerate cosmic rays up to the highest energies.

In this work we investigate the possibility of explaining the very end of the energy spectrum of cosmic rays (above $10^{19.5}$ eV) as measured by the Pierre Auger Observatory by a single source scenario. We use Monte Carlo simulations of cosmic-ray propagation and study different features of the potential single source including its distance, spectral index or mass composition. We are looking for such features of the source that would create an energy spectrum compatible with the measurements. We apply additional requirements on the mass composition on Earth based on measurements by the Pierre Auger Observatory. Older results of this research were previously introduced in [2]. In this proceeding we report new results obtained with updated data of the energy spectrum by the Pierre Auger Observatory and new simulations.

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2 Simulated data

2.1 Simulation of cosmic ray propagation

Simulations of cosmic ray propagation are performed using CRPropa 3 [3]. One-dimensional mode of propagation is used, where only particle interactions are taken into account and no deflections in magnetic fields are applied. Four types of particles are simulated; proton, helium, nitrogen and iron nuclei each with statistics of 10,000 particles. Particles undergo interactions with cosmic microwave background (CMB) and extragalactic background light (EBL). The Gilmore12 model of EBL [4] is used in our simulations. The interactions of cosmic rays with CMB and EBL include photo-pion production, electron pair production and photodisintegration in case of cosmic rays heavier than proton. Other processes included in the simulations are nuclear decay of unstable nuclei and cosmological redshift accounting for the expansion of the Universe. The mass composition on the source is investigated in discrete steps of 10% in the relative fraction of individual particle species.

A single source is considered at distances from 3 Mpc up to 100 Mpc with a step of 1 Mpc up to 20 Mpc and a step of 10 Mpc further out. The energy spectrum on the source is simulated in the energy range from $10^{19.5}$ eV up to $10^{20.5}$ eV as a power law with rigidity dependent exponential cutoff as

$$\frac{dN}{dE} = E^{-\gamma} \cdot f_{\text{cut}}, \quad (1)$$

where γ is the spectral index and f_{cut} is the rigidity exponential cutoff function defined for a given value of rigidity cutoff R_{cut} as

$$f_{\text{cut}} = \begin{cases} 1 & (E < ZeR_{\text{cut}}) \\ \exp\left(1 - \frac{E}{ZeR_{\text{cut}}}\right) & (E > ZeR_{\text{cut}}) \end{cases}, \quad (2)$$

where Z is the proton number of the particle species, see e.g. [5]. The spectral indices of the energy spectrum are considered in the range $\gamma \in (1, 3)$ with a step of 0.5. We investigate the rigidity cutoff from $\log_{10}(R_{\text{cut}}/\text{V}) = 20.5$ with discrete steps of 0.1 down to $\log_{10}(R_{\text{cut}}/\text{V}) = 18.5$. For lower R_{cut} values the energy spectrum above $10^{19.5}$ eV is dominated by the exponential behavior of the generated energy spectrum for all particle species considered.

2.2 Comparison of MC with data

We compare the energy spectra obtained from our simulations with the energy spectrum of cosmic rays above $10^{19.5}$ eV measured by the Pierre Auger Observatory [6]. We take into account the statistical errors of the measured spectrum and statistical errors obtained from the simulations. We compare the two energy spectra based purely on the shape of the measured spectrum. For that purpose, we rescale the measured values of the energy spectrum in such a way that the value in the lowest energy bin is equal to 1 and the simulated energy spectrum is rescaled in the same manner. Therefore, the values are equal in the first energy bin and we calculate a reduced χ^2 for the rest of the energy bins. This is done separately for each spectrum from simulations obtained from a source with given distance, spectral index, mass composition and rigidity cutoff. The agreement between data and simulations is based on two conditions. The first condition is given by $\chi^2/ndf \leq 2$ and the second condition is that the simulated energy spectrum must contain particles in all investigated energy bins.

The measured energy spectrum is not the only information we have about UHECRs, therefore, we can further restrict the single source features. Additional condition is put on the mass composition of the cosmic rays arriving on the Earth based on measurements by the Pierre Auger Observatory [7, 8]. We take into account interpretation of the data measured by the Pierre Auger Observatory using EPOS-LHC and Sibyll 2.3c models of hadronic interactions. QGSJet II-04 model is not taken into account as it suggests nonphysical values of the variance of mean X_{max} . For that reason, we restrict ourselves to cases with the mean mass composition on the Earth above $10^{19.5}$ eV heavier than nitrogen, e.i. $\langle \ln A \rangle > \ln(14)$ and the variance of the mean $\ln A$ to be smaller than 0.5. Further support for heavy composition at the highest energies was also shown in [9].

3 Possible properties of a single source at the highest energies

When comparing the measured energy spectrum with the simulated energy spectra produced by a single source with different parameters of spectral index, mass composition, rigidity cutoff and source distance without the condition on heavy mass composition above $10^{19.5}$ eV a large set of

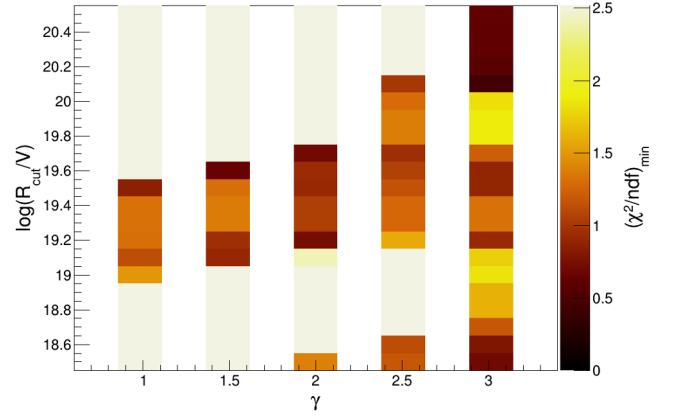


Figure 1. Minimal value of χ^2/ndf between the simulated and measured energy spectra for different combinations of spectral indices and rigidity cutoff values.

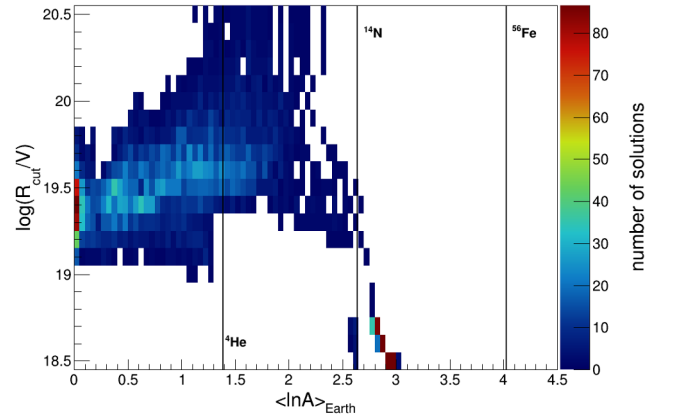


Figure 2. Number of solutions for different values of R_{cut} with respect to mean mass composition on the Earth.

possible features of a single source is obtained. Figure 1 shows the minimal value of χ^2/ndf for different combinations of rigidity cutoff and spectral index of the source. For spectral index $\gamma = 3$ the energy spectrum can be described well in the whole range of investigated R_{cut} values. In case of low spectral indices ($\gamma = 1.0$ and $\gamma = 1.5$), the energy spectrum above $10^{19.5}$ eV can be described well only for a narrow set of rigidity cutoff values in the range $R_{\text{cut}} \approx (10^{19.0} - 10^{19.6})$ V.

The number of solutions, satisfying condition on the compatibility of the energy spectrum with measurement, for different R_{cut} values with respect to the mean mass composition on the Earth are depicted in Figure 2. For the whole investigated phase space of parameters no possible solutions of the source features are found to obtain a very heavy composition (close to iron) on the Earth. A large number of solutions can be found in the region of mass composition close to proton for rigidity cutoff values between $R_{\text{cut}} \sim 10^{19.1}$ V and $R_{\text{cut}} \sim 10^{19.8}$ V. With increasing mass composition on the Earth, rigidity cutoff values of the source are allowed up to the maximum investigated value $R_{\text{cut}} = 10^{20.5}$ V. However, the solutions of the heav-

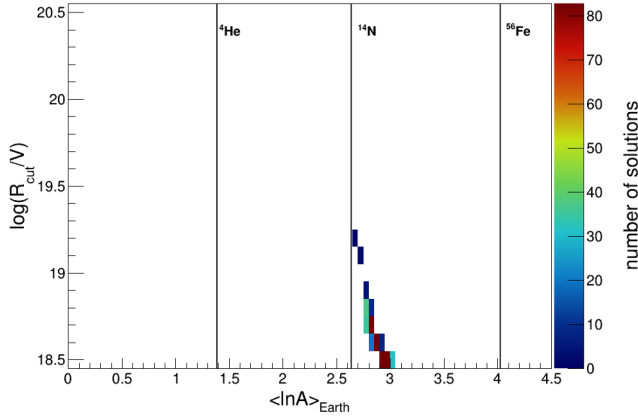


Figure 3. Number of solutions for different values of R_{cut} with respect to mean mass composition on the Earth after applying additional mass composition cuts.

iest mass compositions found are only for rather smaller values of R_{cut} .

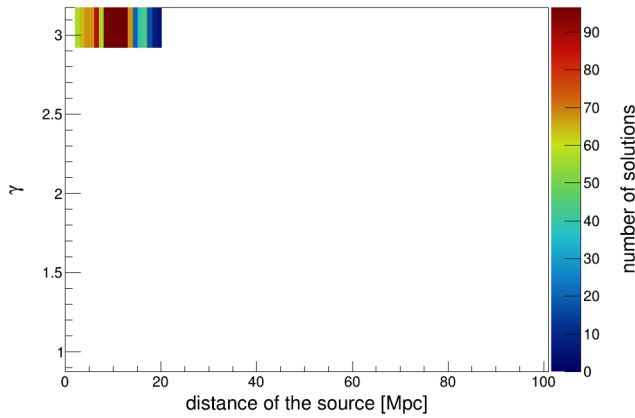


Figure 4. Number of solutions for different values of spectral indices γ with respect to distance of the source after applying additional mass composition cuts.

Without the additional conditions on mass composition a large set of combinations of single source features is allowed in order to explain the shape of the measured energy spectrum. However, restricting ourselves to the cases of $\langle \ln A \rangle > \ln(14)$ and $\sigma(\ln A) < 0.5$ significantly restricts the possible single source features. The number of solutions for different values of R_{cut} with respect to mean mass composition on the Earth after applying additional mass composition cuts are shown in Figure 3. Only sources with $R_{\text{cut}} \leq 10^{19.3}$ V are able to describe both the energy spectrum and mass composition well. Such low values of R_{cut} are needed in order to sufficiently suppress the presence of light elements in the energy spectrum above $10^{19.5}$ eV. The number of remaining solutions are plotted for different spectral indices with respect to distance of the source in Figure 4. This exhibits that a single source describing well both the energy spectrum and mass composition of cosmic rays above $10^{19.5}$ eV measured by the Pierre Auger Observatory should have a spectral index $\gamma \approx 3$ and its dis-

tance should be within 20 Mpc from the Earth. Sources at distances farther are problematic as the longer trajectory causes disintegration of the heavy elements thus pushing the $\langle \ln A \rangle$ lower than required in this work.

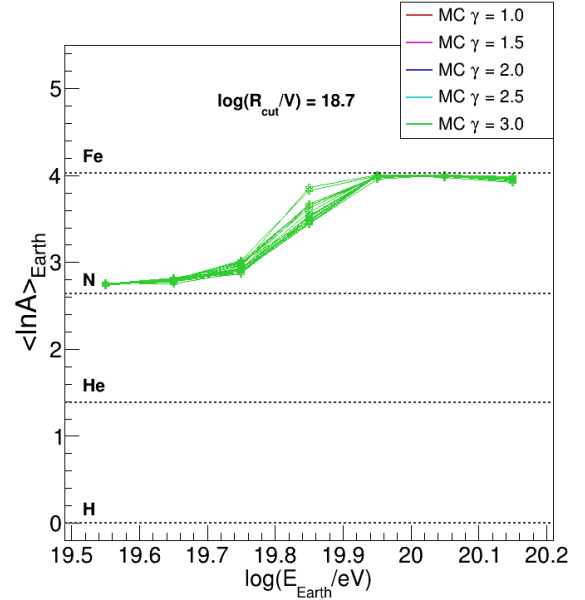


Figure 5. Evolution of the mean mass with energy for solutions found for $R_{\text{cut}} = 10^{18.7}$ V satisfying restrictions put on energy spectrum and mass composition from the measurements.

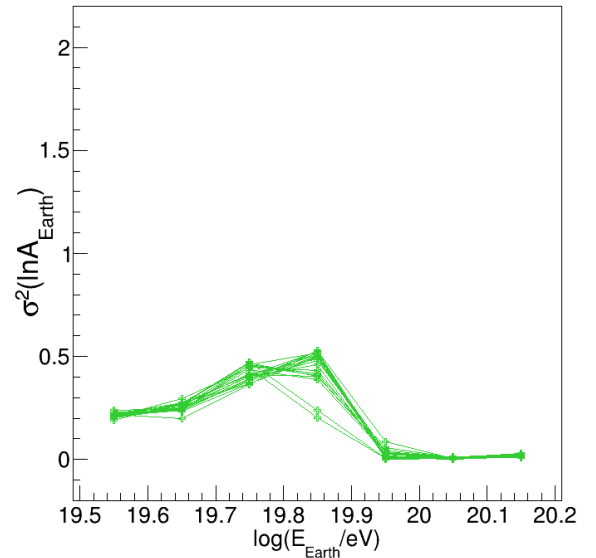


Figure 6. Evolution of the variance of mass with energy for solutions found with $R_{\text{cut}} = 10^{18.7}$ V satisfying restrictions put on energy spectrum and mass composition from the measurements.

An example of the evolution of the mean mass with the energy and the variance of the mass with energy for the solutions found for $R_{\text{cut}} = 10^{18.7}$ V are demonstrated in Figure 5 and Figure 6, respectively. The mean mass composition grows with energy from a composition little heavier

than nitrogen at $E = 10^{19.5}$ eV up to a composition close to pure iron at the highest energies. The small mixing of the elements can be seen in Figure 6 showing a small variance of the mean mass.

4 Conclusions

We investigated the possibility of explaining the energy spectrum measured by the Pierre Auger Observatory above $10^{19.5}$ eV by a single source. Numerical simulations of the energy spectrum created by a single source of various properties including distance, spectral index, mass composition and rigidity cutoff are compared with the measured energy spectrum above $10^{19.5}$ eV by the Pierre Auger Observatory. Additional condition is put on the mean mass composition $\langle \ln A \rangle$ of the cosmic-ray mix and on the variance of the mean mass $\sigma(\ln A)$ based on current measurements by the Pierre Auger Observatory. We show that a single source scenario is able to create an energy spectrum and mass composition compatible with measurements. In order to reproduce well both the energy spectrum and mass composition, such a source should be within 20 Mpc from the Earth. Note that this is an "effective" distance of the source as deflections of cosmic rays in magnetic fields are not taken into account in the simulations. Moreover, such a source should have a spectral index $\gamma \approx 3$ and rigidity cutoff of the source should be $R_{\text{cut}} \leq 10^{19.3}$ V.

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