DOI: 10.1051/epjconf/202328004002

Astrophysical interpretation of Pierre Auger Observatory measurements of the UHECR energy spectrum and mass composition

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Abstract. We present a combined fit of a simple astrophysical model of Ultra-high-energy cosmic-ray sources to both the energy spectrum and mass composition data measured by the Pierre Auger Observatory. The astrophysical model we adopted consists of identical sources uniformly distributed in a comoving volume, where nuclei are accelerated with a rigidity-dependent mechanism. The fit has been performed at first for energies above 5 EeV, i.e., the region of the all-particle spectrum above the so-called "ankle" feature, and has then been extended to lower energies in order to include this feature. The fit results and their astrophysical implications in both cases are discussed.

1 Introduction

The Pierre Auger Observatory [1] is the largest facility to detect cosmic rays built so far. It is located in the province of Mendoza, Argentina, and has been in operation since 2004, studying cosmic rays by combining different experimental techniques.

The Pierre Auger Collaboration has studied the features of the all-particle energy spectrum with unprecedented precision. Far from being described by a simple power law, in the highest-energy region, the all-particle cosmic-ray spectrum shows several features [2, 3]: a sharp feature, known as the ankle, is observed at $10^{18.7}$ eV, corresponding to a hardening of the spectrum. A new feature, dubbed the instep, at $10^{19.1}$ eV, could reflect the interplay of light-to-intermediate nuclei. Finally, a suppression of the total flux above $10^{19.7}$ eV may be attributed to energy losses during the propagation of ultra-high energy cosmic rays (UHECRs) [4, 5], to the limited maximum energy the sources can provide to particle acceleration, or possibly to a combination of both effects.

The composition of the UHECRs [6, 7], as estimated from the distributions of the depth of maximum development of the showers X_{max}, appears to be given from a mix of protons and medium-mass nuclei (e.g. nitrogen) at energies above the second knee, gradually getting lighter with increasing energy up to $10^{18.3}$ eV. The total UHECR spectrum may consist of the superposition of alternating groups of elements with progressively heavier mass, each with a steep cutoff, but with increasingly sparse statistics towards the suppression region. This is

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supported by the observation that the mass composition above the ankle appears heavier and less mixed. Despite the accurate measurement of the energy spectrum, an interpretation in terms of sources is ambiguous. Using both the spectrum and composition, one can remove this degeneracy and infer information about the source scenarios which are compatible with data. Several investigations have been done in recent years to interpret the UHECR spectrum and composition. Most of these studies converge to scenarios with sources injecting hard spectra with low rigidity cutoff and mixed composition, even though simplifying assumptions are used, such as uniform source distributions and 1D cosmic ray propagation. The Pierre Auger Collaboration has published a comprehensive study about the astrophysical implications from the combined fit of spectrum and composition data above the ankle [8], discussing in detail the effects of theoretical uncertainties on propagation and interactions in the atmosphere of UHECRs as well as the dependence of the fit parameters on the systematic experimental uncertainties. In this study, we used a scenario in which the sources of UHECRs are of extragalactic origin and accelerate nuclei in electromagnetic processes with a rigidity-dependent maximum energy $E_{max}(Z) = E_{max}(p) \cdot Z$, where Z denotes the charge and $E_{max}(p)$ is the maximum energy for protons.

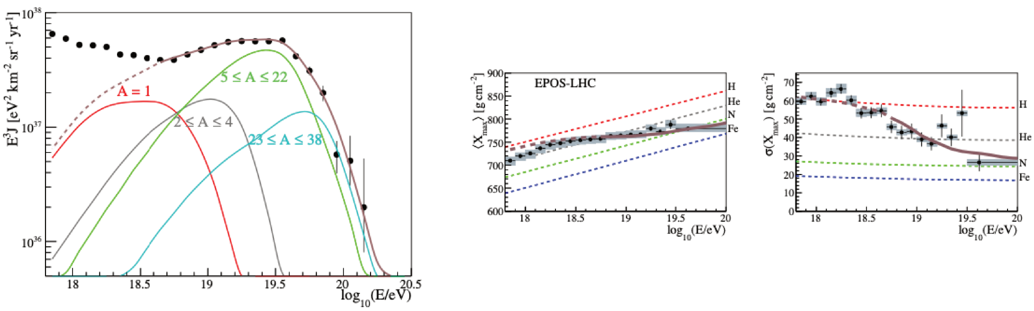

Figure 1. *Left*: Energy spectrum obtained with the best-fit parameters for [8]. Partial spectra are shown with different colors, total spectrum with brown. Full circles show the experimental spectrum. *Right*: average and standard deviation of the X_{max} for data (full circles) and best-fit prediction (brown). Pure H (red), He (grey), N (green) and Fe (blue) are shown as dashed lines. Only the energy range where the brown lines are solid is included in the fit. From [8].

Within this scenario, a good description of the shape of the measured energy spectrum, as well as the energy evolution of the X_{max} distributions can be achieved, as shown in Fig. 1, if the sources accelerate a primary nuclear mix consisting of H, He, N and Si. In addition, the primary spectrum has to follow a power law $\propto E^{-\gamma}$ with a spectral index $\gamma \simeq 1$, and the maximum energy of protons has to be about $10^{18.7}$ eV. The mass composition at the sources is dominated by intermediate-mass nuclei (N, Si). Using different hypotheses concerning the extragalactic propagation (more details can be found in [8]), the spectral index and the maximum energy can change considerably and, for some of them, well outside the statistical uncertainties of the fit with other assumptions. However, the hard spectral index and low rigidity cutoff solution are generally preferred.

2 The extended combined fit

In order to provide an astrophysical interpretation of the ankle feature, the fit was extended to lower energies [9]. The simplest extension of this sort consists of introducing a supplemental extragalactic component at low energy, characterized by different physical parameters with respect to the one being dominant above the ankle: from an astrophysical point of view, such a component may originate from a different population of sources. Combining the two contributions, it is possible to have a description of the data including the ankle feature, as shown in the left panel of Fig. 2. The high-energy extragalactic component is qualitatively in agreement with the one found in [8] when fitting only data above $10^{18.7}$ eV, hence the above-ankle fit results are not spoiled by this extension to lower energies.

In this framework, the possibility of including the end of a Galactic contribution at low energies was also explored (right panel of Fig. 2). It was found that a Galactic component made of heavy elements is strongly disfavoured by the composition data, while the best fit was found attributing intermediate-mass to the Galactic spectrum. The presence of a Galactic intermediate-mass contribution, in this case represented by nitrogen, is difficult to accommodate with respect to the standard acceleration in our Galaxy. Nonetheless, such a scenario could be explained by considering an additional Galactic contribution provided by the Wolf-Rayet stars [10], which could actually accelerate nitrogen nuclei up to energies of the order of 10^{18} eV. A detailed discussion of both astrophysical scenarios can be found in [9].

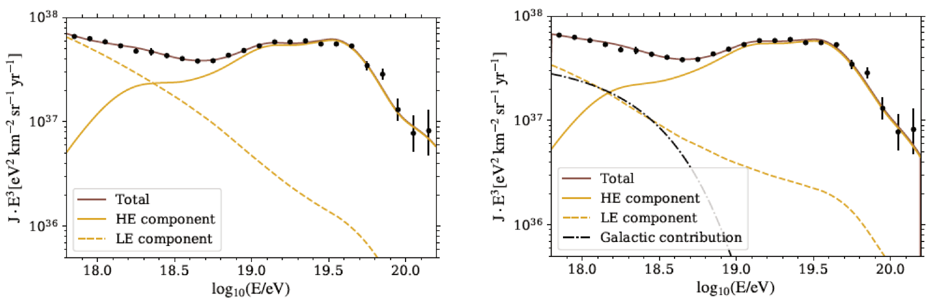

Figure 2. *Left*: The expected low-energy and high-energy contributions in the assumption of pure extragalactic contribution, here shown as dashed and solid lines, respectively. *Right*: The expected low-energy and high-energy contributions, as well as the expected end of the Galactic spectrum, in the assumption that this influences the cosmic-ray flux in the energy region of interest.

3 The sub-ankle proton fit

A complementary approach to extend the combined fit detailed in section 1 was exploited in [11]. For energies between $10^{17.8}$ eV and $10^{18.7}$ eV, only the observed fluxes of protons are fitted, as shown with red dots in the left plot of Fig. 3, while at energies above $10^{18.7}$ eV the procedure is identical to [8]. It was found that including the proton component at low energies significantly worsens the deviance, while considering an additional parameter in the procedure, i.e. the spectral index for protons, the reduced chi-square is compatible with the case exploited in [8]. The best-fit energy spectrum, as well as the experimental data, are illustrated in Fig. 3, while the best-fit parameters are listed in Table 1 of [11].

The fit simultaneously requires a soft spectral index for protons and a hard injection spectrum for intermediate and heavy nuclei at the highest energies. Remarkably, such behavior qualitatively corresponds to scenarios of in-source interactions. In this scenario, the photodisintegration process acts as a high-pass filter allowing the highest energy cosmic-ray nuclei to escape unscattered, whereas the lowest energy ones are disintegrated inside the

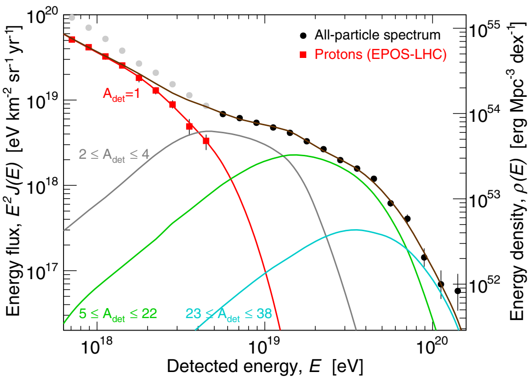

Figure 3. Energy flux at Earth as a function of energy, as modeled by the best-fit parameters for the benchmark scenario. The all-particle spectrum and proton component are shown as black circles and red squares, respectively [11]. Lighter points are not included in the fit. The best-fit components obtained for five detected mass groups are displayed with solid colored lines, as labeled in the Figure. The energy flux of the heaviest mass group, with detected mass number in 39–56, is below the range of interest.

source region, thereby generating a pile-up of nucleons with energy scaling as $1/A$, being A the mass of the nucleus injected in the acceleration region, producing hard ejection spectra for nuclei below the maximum rigidity and generate secondary neutrons at lower energies [12]. These results provide a solid base for constraining the spectral indices for protons and nuclei, as well as the energetics of the sources and the abundances of elements in their surroundings.

Future observations will help us to corroborate the importance of in-source interactions for the interpretation of UHECR data, as shown in this section, or to call for alternative interpretations, such as two extragalactic components from different types of sources, as presented in section 2. For this quest, the upgraded instrumentation of the Pierre Auger Observatory in the next years [13] could play a major role.

References

[1] Aab, A. et al. [Pierre Auger Collaboration] , NIM A **798**, 172-213 (2015)
[2] Abreu, P. et al. [Pierre Auger Collaboration], EPJC **81**, 966 (2021)
[3] Aab, A. et al. [The Pierre Auger Collaboration], Phys. Rev. Lett. **125**, 121106 (2020)
[4] Greisen, K., Phys. Rev. Lett. **16**, 748 (1966)
[5] Zatsepin, G. T. and Kuzmin, V. A., JETP Lett. **4**, 78 (1966)
[6] Aab, A. et al. [The Pierre Auger Collaboration], Phys.Rev. **D90** 122006 (2014)
[7] Bellido, J. and Pierre Auger Collaboration, PoS ICRC2017, 506 (2018)
[8] Aab, A. et al. [The Pierre Auger Collaboration], JCAP**04**, 038 (2017)
[9] Halim, A. et al. [The Pierre Auger Collaboration], arXiv:2211.02857.
[10] Thoudam, S. et al. , A&A **A33**, 595 (2016)
[11] Luce, Q. et al. , *ApJ* **936**, 62 (2022)
[12] Unger, M. et al., Phys. Rev. **D 92**, 123001 (2015)
[13] Castellina, A. et al [Pierre Auger Collaboration] , EPJ Web Conf. **210**, 210 (2019)