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IMPLICATIONS OF THE COSMIC RAY SPECTRUM FOR THE MASS COMPOSITION AT THE HIGHEST ENERGIES

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Abstract. The significant attenuation of the cosmic-ray flux above $\sim 5\,10^{19}$ eV suggests that the observed high-energy spectrum is shaped by the so-called GZK effect. This interaction of ultra-high-energy cosmic rays (UHECRs) with the ambient radiation fields also affects their composition. We review the effect of photo-dissociation interactions on different nuclear species and analyze the phenomenology of secondary proton production as a function of energy. We show that, by itself, the UHECR spectrum does not constrain the cosmic-ray composition at their extragalactic sources. While the propagated composition (i.e., as observed at Earth) cannot contain significant amounts of intermediate mass nuclei (say between He and Si), whatever the source composition, and while it is vastly proton-dominated when protons are able to reach energies above 10^{20} eV at the source, we show that the propagated composition can be dominated by Fe and sub-Fe nuclei at the highest energies, either if the sources are very strongly enriched in Fe nuclei (a rather improbable situation), or if the accelerated protons have a maximum energy of a few 10^{19} eV at the sources. We also show that in the latter cases, the expected flux above $3\,10^{20}$ eV is very much reduced compared to the case when protons dominate in this energy range, both at the sources and at Earth.

1 Introduction

The measurement of the composition of ultra-high-energy cosmic-ray (UHECRs) and the inference of their source composition are among the main questions involved in the understanding of their enigmatic origin. The common hypothesis is a transition from a heavy composition to a light composition between 10^{17} eV and a few times 10^{18} eV. The shape of the GZK feature which results in a flux suppression and the energy at which it occurs could restrain the composition. In this paper we investigate the constraints placed by these observables on the source composition as well as on that expected at Earth.

2 The method : Nuclei propagation in the Universe

We model the propagation of all nuclei from a uniform and continuous distribution of sources. Departing from a given redshift, z = 5, we consider them propagating, facing photonic background of CMB and IR/Optical/UV. Computing all relevant photodisintegration mean free paths for each interaction process, we finally derive all the interactions experienced by nuclei. Pair production [Rachen 1996] and adiabatic losses result in a decrease of the Lorentz factor of the nucleus, whereas photodisintegration processes trigger the ejection of several nucleons from the parent nucleus, which make a critical difference with the well known proton case. The lowest energy (10-20 MeV) disintegration process is the Giant Dipole Resonance (GDR). Around 30 MeV the quasi-deuteron (QD) process becomes comparable to the GDR and dominates the total cross section at higher energies. Finally, the photopion production of nuclei becomes relevant above 150 MeV.

3 Results : spectrum predictions for various source composition hypotheses

We turn to the calculations of propagated spectra assuming various source compositions. The propagated spectra that best fit Auger spectra for pure He, CNO and Si source compositions are shown in the present

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paper. These extreme examples show that for light or intermediate source composition, the spectrum after propagation is expected to be rich in proton and that a large proton abundance observed above a few 10^{19} eV would not strongly constrain the source composition.

The case of a heavy source composition

The case of a heavy source composition (pure Fe) is displayed in Fig. 1. It can provide good fits as well to the data ($\beta = 2.3$ for Auger) though the shapes are different from the proton cases. One can see that the expected composition is still heavy on Earth with a low abundance of secondary protons. The implication of a heavy source composition on the composition at the Earth is then very different from the other cases we studied, but current data do not allow us to distinguish between the proton dominated and the heavy dominated shapes.

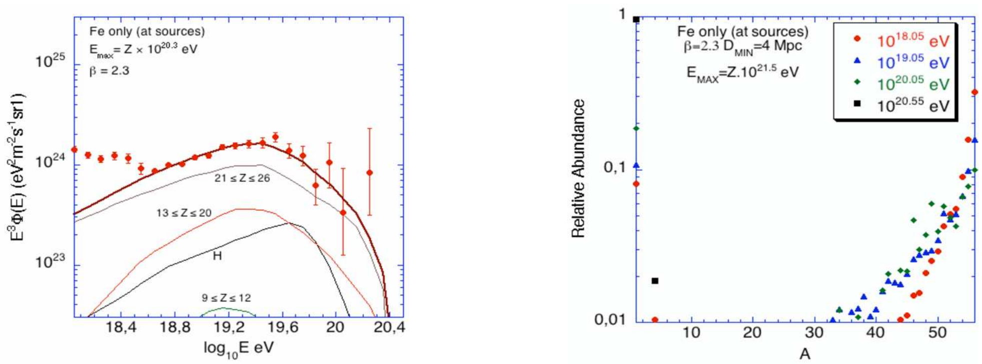

Fig. 1. Propagated spectra obtained assuming a pure iron source composition compared to Auger spectra (left) and relative abundances of the different isobar between A=1 and 56, expected on Earth in four different energy bins (right).

Another surprising yet acceptable fit

Acceptable fits of the data can be obtained with a mild increase of the overall abundance of heavy elements at the source. With $E_{max} = Z \times 4\,10^{19}$ eV and $\sim 30\%$ of Fe nuclei at the sources, one can see [Decerprit & al, 2008] that the agreement with data is reasonable and that the composition, proton dominated at low energy, becomes gradually heavier and very dominated by Fe above 50 EeV.

4 Discussion & conclusion

In this paper, we extract conclusive results about the UHCER composition from the data. In the case of a source composition dominated by protons or light nuclei, we always derive a good fit of the data and a propagated composition enriched in protons, as well as a GZK-like cut-off. If heavy nuclei are present at the source, the proton enrichment is expected to stop between $\sim 5\,10^{19}$-$\sim 2\,10^{20}$ eV, so that it leaves a distinctive signature on the elongation rate [cf. Allard 2007]. In the case of heavy source compositions, conclusions are radically different but fits remain compatible with current data and show propagated spectra dominated by heavy nuclei. Finally, we have shown that current experimental spectra are compatible either with proton-dominated UHECRs or with the "nuclear GZK cut-off" coming from the photodisintegration of heavy dominated UHECRs. Though current data do not allow to distinguish between them, it is likely that future data, as expected from the Pierre Auger observatory, will provide better constraints.

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