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Signatures of the extragalactic cosmic-ray source composition from spectrum and shower depth measurements

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Abstract: We discuss the differences induced by the assumed composition of extragalactic sources on the predicted UHECR spectrum and the energy evolution of $\langle X_{\max}\rangle$, i.e. the mean value of the atmospheric depth at the cosmic-ray air shower maximum. We show that for the different assumptions on the source power evolution, in the case of a mixed composition, the ankle can be interpreted as the end of the transition from galactic to extragalactic cosmic rays. We show that the features in the shape of $\langle X_{\max}\rangle$(E) associated with this cosmic-ray source model are essentially independent of the assumed hadronic model. A signature of the interactions of nuclei with the photon backgrounds is also expected above 10^{19} eV. The comparisons with Stereo HiRes and Fly's Eye data favour an extragalactic mixed composition and the corresponding interpretation of the ankle. Confrontation of model predictions with future data at the highest energies will allow a better determination of the transition features and of the cosmic-ray source composition.

Introduction

The so-called galactic/extragalactic transition has been recognized recently as a key issue, because its actual energy range and composition structure are interrelated and contain important information about both the Galactic cosmic-ray (GCR) and extragalactic cosmic-ray (EGCR) components. On the one hand, cosmic rays above $\sim 10^{19}$ eV are generally thought to be of extragalactic origin, notably because they seem to be dominated by proton (see e.g. Abbassi et al., 2005) which would either not be confined by the Galactic magnetic fields or give rise to anisotropies associated with the Galactic plane in excess of the current upper limits. On the other hand, the Galactic origin of low-energy cosmic rays – say below 10^{17} eV – is also widely accepted. The KASCADE experiment estimated the cosmic ray flux and composition between 10^{15} and 10^{17} eV [1], confirming the so-called *knee* feature in the spectrum at $E_{\rm knee} \simeq 4\,10^{15}$ eV and showing a transition towards muon-richer cosmic-ray showers at higher energy interpreted as a signature of heavier primary nuclei, independently of the assumptions relating to the underlying hadronic model used to simulate the development of CR-induced showers. The CR composition thus appears to become heavier and heavier between $E_{\rm knee}$ and 10^{17} eV. However, detailed composition measurements by KASCADE are hadronic model dependent and a fully consistent picture of the measured properties of air showers in the knee region has not been reached yet. Therefore, a number of different interpretations of the knee remain compatible with the observations and as a consequence several models accounting for the emerging extragalactic component and implying different energy ranges for the GCR/EGCR transition are currently viable. The different models of GCR/EGCR transition have very different implications for the phenomenology of UHECRs and the interpretation of the ankle, with direct impact on the inferred composition and spectral index of the supposedly power-law source spectrum of EGCRs. The energy evolution of the mean value of the atmospheric depth at air shower maximum, $\langle X_{\max}\rangle$, is a powerful tool to study changes in composition at the highest energies. Although the interpretation of the measured values of $\langle X_{\max}\rangle$ in terms of mass composition is hadronic model dependent, the global shape of the evolution of $\langle X_{\max}\rangle$ with energy (e.g. inflections and/or abrupt changes) is largely model-independent and can thus be directly confronted with the predictions of the different transition models. In this paper, we calculate simultaneously the extragalactic spectrum and $\langle X_{\max}\rangle$ evolution associated for the mixed composition scenario we introduced in [2] and discuss its distinctive signatures.

Propagated cosmic-ray spectra and the shape of $\langle X_{\max}\rangle$(E)

For each source evolution hypothesis (see [4] and reference therein), we calculate the propagated extragalactic spectra using the latest version of our code described in detail in [5]. In each case, we determine the value of the spectral index β providing the best fit of the high-energy CR data and infer the corresponding galactic component by merely subtracting the propagated EGCR component from the measured flux. For definite predictions concerning the CR composition across the Galactic-extragalactic transition, we assume that this remaining GCR component is essentially made of iron nuclei above $10^{17.5}$ eV. The propagated EGCR spectra obtained with a mixed source composition are shown in Fig. 1a. The best fit of the high-energy data is obtained in these cases for significantly smaller spectral indices, i.e., harder source spectra than in the pure proton case: $\beta \simeq 2.3$ in the uniform case, going down to 2.2 for SFR-like source evolution and 2.1 for the strong evolution model. In all these mixed composition cases, the end of the GCR/EGCR transition roughly coincides with the ankle [2, 6]. Above $10^{18.5}$ eV, the predicted spectrum is quite insensitive to the source distribution. It is also important to note that the mixed composition models do not imply/require any definite value of the highest energy of cosmic rays in the Galactic component, as long as GCRs represent a sufficiently small fraction of the total spectrum around E_{ankle} not to influence the overall spectrum and composition. Therefore, the Galactic component does not necessarily vanish above $E_{\rm ankle}$, nor is it required that cosmic rays be accelerated above $E_{\rm ankle}$ at all. At energies below the ankle, the inferred fraction of GCRs depends on the source evolution model, just as in the pure proton case.

The *propagated* EGCR composition is a direct output of our computations, and we assume that the Galactic component is essentially made of Fe nuclei above $10^{17.5}$ eV. From the relative abundance of all elements at a given energy, we derive the average value of the atmospheric depth (in g/cm^2) at which the maximum shower development is reached, $\langle X_{\max}\rangle$, using Monte-Carlo shower development simulations. We have used 25000 CONEX air showers and different hadronic models. Results obtained with QGSJet-II are displayed on Fig. 1b for mixed composition models. The case of mixed composition models is illustrated in Fig. 1b. The evolution of $\langle X_{\max}\rangle$ is relatively steep in the transition region, below E_{ankle}, because the composition evolves rapidly from the dominantly heavy Galactic component to the light extragalactic mixed composition. However, the evolution is significantly slower than in the case of Second Knee Transition models, because the transition is wider and the cosmic-ray composition does not turn directly into protons only. An intermediate stage appears, which may be called the mixed-composition regime, where a break in the evolution of $\langle X_{\max}\rangle$ around E_{ankle} is followed by a flattening up to $\sim 10^{19}$ eV, reflecting the fact that the (propagated) EGCR composition does not change much in this energy range. This is because among the different EGCR nuclei, only He nuclei interact strongly with infrared photons at these energies. Between E_{ankle} and $\sim 10^{19}$ eV, the evolution of $\langle X_{\max}\rangle$ is actually compatible with what is expected from a constant composition. Then around 10^{19} eV, the relative abundance of nuclei heavier than protons starts to decrease significantly as a result of photo-disintegration processes: the CNO component starts interacting with the infrared background and the CMB photons eventually cause the He component to drop off completely. The evolution of $\langle X_{\max}\rangle$ therefore steepens again, accompanying the progressive evolution towards an almost pure proton composition as each type of nuclei reaches its effective (mass dependent) photo-disintegration threshold. Even though slight differences may be expected from one model to the other, the above evolution of

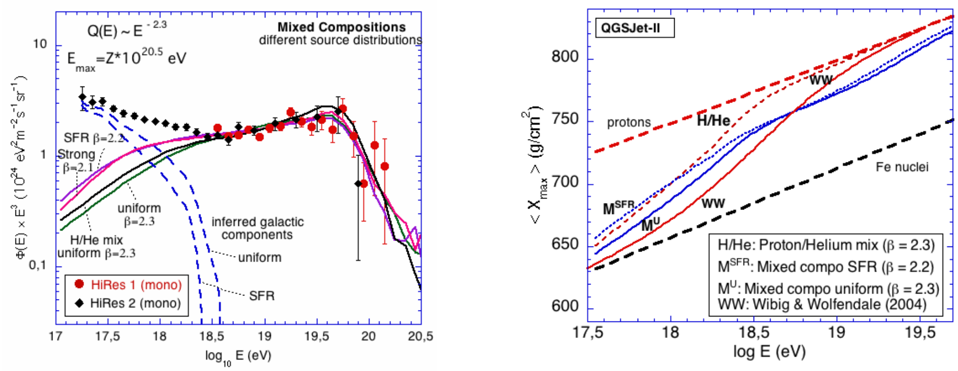

Figure 1: Left : Propagated spectra, $E^3\Phi(E)$, for mixed composition models (generic mix of nuclei and primordial H-He mix) compared with HiRes monocular data (Bergman et al., 2005). Different source evolution models are indicated by the labels. The corresponding galactic components are inferred from the overall spectrum by subtracting the EGCR component, in the case of the uniform and SFR source evolution models (the other two cases are omitted for clarity). Right : Evolution of $\langle X_{\max}\rangle$ as a function of energy (using QGSJet-II) for mixed composition EGCR sources (generic and primordial) with two different source evolution scenarios (M^{U} and $\mathrm{M}^{\mathrm{SFR}}$). The scenario of Wibig and Wolfendale model [3] is also displayed for comparison (WW).

$\langle X_{\max}\rangle(E)$ in a three steps process is a characteristic prediction of mixed-composition models, or generically of any type of EGCR sources allowing for the acceleration of a significant fraction of nuclei heavier than He [6]. In addition to this specific signature associated with the GCR/EGCR transition, mixed-composition models can be characterised by another interesting feature appearing at the highest energies. Indeed, if Fe nuclei are accelerated above 10^{20} eV, the cosmic-ray composition is expected to become somewhat heavier again above $5\,10^{19}$ eV, where protons start to experience the usual GZK effect (i.e., photo-pion production over CMB photons). At this energy, heavy nuclei only interact with the infrared photons, which results in a much gentler attenuation of the heavy components than that of the protons, i.e. a heavier composition. This relative increase of the heavier component ceases around 1.5–2 10^{20} eV, where interactions with the CMB photons via the GDR process take over and photodissociate the heavy nuclei very quickly. From the point of view of the $\langle X_{\max}\rangle$ evolution, a second flattening is thus expected between $5\,10^{19}$ eV and $1.5\,10^{20}$ eV, followed by a final steepening towards a pure proton composition, as can be seen clearly on Fig. 2b. The actual amplitude of this feature obviously depends on the relative abundance of heavy nuclei accelerated at the highest energies, which may allow one to constrain this very important part of the EGCR injection spectrum, should such a feature be observed in the future. While the current data above $5\,10^{19}$ eV are too scarce to test this prediction, we expect future experiments to extend composition analyses up to the highest energies, thereby helping discriminate among the EGCR source models. Careful measurements of the $\langle X_{\max}\rangle$ evolution at the highest cosmic-ray energies should provide an unambiguous way to discriminate between GCR/EGCR transition models (see also [6, 4]). The currently available data do not allow one to draw definitive conclusions yet. However, we argued in [6] that the predictions of the mixed-composition models appear to be in better agreement with the current data from fluorescence detectors. In particular, a good agreement is found with Fly's Eye results above $10^{17.5}$ eV [7]. Concerning the slope of the $\langle X_{\max}\rangle$ evolution in the transition region (i.e., below the ankle), mixed-composition models typically predict of value between 85 and 105 g/cm^2/decade (depending on the hadronic model and the source evolution hypothesis), which is compatible with the value of 93 g/cm^2/decade reported by the HiRes-

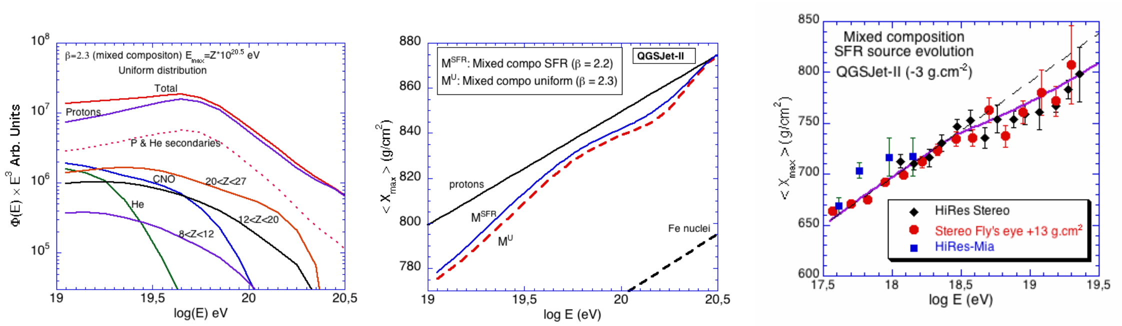

Figure 2: Left: Predicted spectrum for a mixed extragalactic composition above 10^{19} eV decomposed in its elemental components. Center: $\langle X_{\max}\rangle$ evolution for an extragalactic mixed composition above 10^{19} eV, for the SFR and uniform source evolution. Right: Predicted $\langle X_{\max}\rangle$ evolution for a mixed composition in the SFR source evolution hypothesis (QGSJet-II slightly rescaled downward by 3 $g\,cm^{-2}$) with Fly's Eye (rescaled upward by 13 $g\,cm^{-2}$), Stereo HiRes and HiRes-Mia.

Mia experiment between 10^{17} and 10^{18} eV [8]. Furthermore, both the predicted break at the ankle and the steepening above 10^{19} eV are compatible with the HiRes Stereo data [9]. Fig. 2c shows the comparison between the $\langle X_{\max}\rangle$ evolution for a mixed composition in the SFR evolution case and the data of HiRes Stereo, HiRes-Mia and Fly's Eye (rescaled by 13 $g\,cm^{-2}$, as suggested by [10]). As can be seen, Fly's Eye and Stereo HiRes data are consistent with the predicted break in the $\langle X_{\max}\rangle$ evolution between 3 and 4 EeV, which also corresponds to the energy of the ankle reported by both experiments. Although the agreement between the experimental data and the predictions of the mixed-composition models is encouraging, more precise and higher statistics measurements are needed. In the near future, the Pierre Auger Observatory and its low energy enhancement ([11], and references therein) should provide accurate measurements of the energy evolution of $\langle X_{\max}\rangle$ which is key to the detailed understanding of high-energy cosmic rays.

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