

# A complete model of the cosmic ray spectrum and composition across the Galactic to extragalactic transition

Noemie Globus

*School of Physics and Astronomy, Tel Aviv University, Tel Aviv 69978, Israel*

Denis Allard and Etienne Parizot

*Laboratoire Astroparticule et Cosmologie, Université Paris Diderot/CNRS,*

*10 rue A. Domon et L. Duquet, 75205 Paris Cedex 13, France*

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We present a complete phenomenological model accounting for the evolution of the cosmic ray spectrum and composition with energy, based on the available data over the entire spectrum. We show that there is no need to postulate any additional component, other than one single Galactic component depending on rigidity alone and one extragalactic component, the characteristics of which are similar to those derived from a study of particle acceleration at mildly relativistic shocks in a gamma-ray burst environment (Globus *et al.*, 2015). In particular, we show that the resulting cosmic ray spectrum and composition satisfy the various constraints derived from the current data in the Galactic/extragalactic transition region, notably from the measurements of KASCADE Grande and Auger. Finally, we derive some generic features that a working phenomenological scenario may exhibit to give a global account of the cosmic ray data with a minimum number of free parameters.

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## I. INTRODUCTION

One century after the discovery of cosmic rays (CRs), their study remains one of the main focuses of high-energy astrophysics. In recent years, an important set of new cosmic ray data has become accessible, thanks to major experimental progresses. The Pierre Auger Observatory (Auger) [1] and Telescope Array (TA) [2] experiments have explored the ultra-high-energy cosmic rays (UHECRs) with unprecedented observational power. Below the ankle, KASCADE-Grande (KG) [3] has made crucial measurements of the cosmic ray spectrum, including a separation between low-mass and high-mass nuclei, which can be linked to measurements in the knee region made in particular by the KASCADE [4] experiment. Below the knee, new data have been available as well, notably from CREAM [5] and TRACER [6] and most recently from PAMELA [7] and AMS [8], allowing a more precise determination of the relative abundances of the various nuclei among the Galactic cosmic rays (GCRs).

These new data allow a more complete description of the CR phenomenology over the entire energy range and in particular at the Galactic/extragalactic (GCR/EGCR) transition, taking into consideration both the CR energy spectrum and the composition. Some recent studies have claimed that the data could not be accounted for without invoking, in addition to the main GCR and extragalactic UHECRs, one or more additional (Galactic or extragalactic) components dominating the flux at intermediate energies, between the knee and the ankle (see, for instance, Refs. [9–12]). In this paper, we argue against such a necessity and explicitly show that the global CR spectrum can be fully described in a natural way within a two-component model, one Galactic and one extragalactic.

We base our model on a very simple and generic description of the GCR component, the properties of which depend only on the rigidity of the particles and on an EGCR component that is directly borrowed from a previous work on particle acceleration at gamma-ray bursts (GRBs) mildly relativistic internal shocks [13], which consistently predicts an evolution of the composition compatible with Auger data. We show that this model provides a fair account of all the significant features of the cosmic ray spectrum and composition from below the knee to the highest energies.

## II. MODEL

### A. Extragalactic component

One of the most important results of Auger is the observation of a transition from a light-dominated to a heavy-dominated composition between a few  $10^{18}$  eV and a few  $10^{19}$  eV [14,15]. As we first proposed in Ref. [16], this can be interpreted as a consequence of an early high-energy cutoff of the protons in the sources, due to an intrinsic limitation of the acceleration process. As long as the acceleration of particles is governed only by electromagnetic processes, all nuclei behave in exactly the same way if they have the same magnetic rigidity. Nuclei of charge  $Z$  are thus expected to reach an energy  $E_{\max}(Z) = Z \times E_{\max}(p)$ , where  $E_{\max}(p)$  is the maximum proton energy. It is thus natural to expect that nuclei of higher and higher mass dominate the UHECR source composition above the maximum energy of the lower-mass nuclei.

In more realistic situations, however, such a simple model should be amended to take into account the energy losses and photo-dissociation processes that may occur in the acceleration site. In a recent study, we developed a

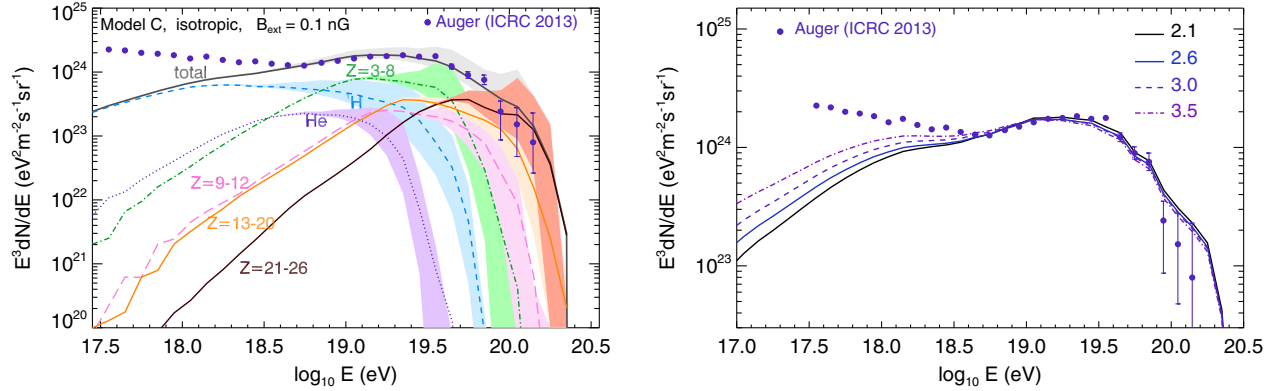


FIG. 1 (color online). Left: EGCR flux as a function of energy for H, He, and different ranges of nuclei (indicated by the charge labels), as predicted by our acceleration model in GRBs, adjusted to the Auger data. The figure was taken from Ref. [13]. Right: Effect on the propagated EGCR spectrum of different assumptions for the cosmological evolution of the source density.

numerical model for the acceleration of UHECRs at GRBs mildly relativistic internal shocks [13]. We showed that the relatively high density of energetic photons in the acceleration site leads to significant photo-dissociation, which has two important consequences: i) the resulting maximum energy of the nuclei is not strictly proportional to  $Z$  but also reflects their photo-dissociation rate; ii) the spectrum of the UHECRs eventually injected by the source into the intergalactic medium is close to a hard power law (roughly in  $E^{-1}$  below  $E_{\text{max}}$ ), but while all composed nuclei have essentially the same spectral index, protons have a significantly steeper spectrum. This is due to the secondary neutrons, which are mostly produced by photodisintegration processes during the acceleration. Indeed, the charged particles mostly escape from the acceleration region in the weak scattering regime, i.e., at the highest energies. On the contrary, the secondary neutrons are not confined by the local magnetic fields and thus escape with their production spectrum (similar to that of the nuclei at the shock, close to an  $E^{-2}$  power law; see Ref. [13]).

The model consistently predicts the shape of the spectra of individual nuclei, including their high-energy cutoff at the source. We then convoluted individual source injection over the GRB luminosity function and used our UHECR propagation code, taking into account energy losses, photo-dissociation, and magnetic deflections [17], to derive the propagated spectrum which can be observed on Earth. The result is shown in Fig. 1, which is taken from Ref. [13], with a comparison to the Auger data. The shaded area corresponds to the so-called cosmic variance and represents the expected range for the flux of the different nuclei, including 90% of independent realizations of the model. As can be seen, the propagated proton spectrum is indeed much softer than that of the other nuclei. This model reproduces fairly well the overall spectrum and shows a clear transition from a proton-dominated composition at the ankle to a Fe-dominated composition at the highest energies.

To limit the number of free parameters, we use this model of the EGCR component in the present study. However, we

allow for different assumptions regarding the cosmological evolution of the sources. Figure 1 shows the total spectrum obtained when the source density increases as a function of redshift as  $(1+z)^\alpha$ , with  $\alpha = 2.1, 2.6, 3.0$ , or  $3.5$ . As expected, a stronger cosmological evolution does not affect the high-energy part of the spectrum [since the contributing sources are all located at low redshifts, due to the Greisen-Zatsepin-Kuzmin (GZK) horizon effect] but implies a larger contribution of the EGCR sources at low energy. Since the corresponding flux is dominated by protons, larger values of  $\alpha$  result in larger contributions of extragalactic protons, which influences the composition at the GCR/EGCR transition. We found that  $3.0 < \alpha < 3.5$  provides the most striking agreement with the composition measurements. In the following, we assume  $\alpha = 3.5$ , which is fully compatible with the observational constraints. In particular, we verified that the gamma-ray emission resulting from the intergalactic showers associated with the propagation of the EGCRs does not violate the measurements made by the Fermi telescope. This necessary condition is fulfilled due to the relatively hard spectrum (roughly  $\propto E^{-2}$ ) and low maximum energy of nucleons (see Fig. 31c of Ref. [13]) injected by the sources (see Ref. [18]). We should, however, note that our results do not necessarily imply that the EGCR sources must have a strong cosmological evolution. Similar changes of the EGCR spectrum could also be obtained by modifying the assumed source luminosity function or the turbulence structure at the shock. Moreover, the assumption that GRBs are the sources of UHECRs is not critical for the success of the model. The key feature on which we rely here is the prediction of a softer spectrum for the protons, which can be expected in other cosmic accelerators as soon as they involve a significant amount of nuclei and the matter or radiation density is large enough in the source environment.

## B. Galactic component

For the GCR component, we assume that all nuclei have the same rigidity spectrum, consisting of a broken

power law with spectral index  $x$  below an energy  $E_{\text{break}}(Z) = Z \times E_{\text{break}}(p)$  and a spectral index  $x + \Delta x$  above that energy, up to an exponential cutoff in  $\exp(E/ZE_{\text{max}})$  above  $E_{\text{max}}$ .

The slope  $x$  and the relative abundance of the various nuclei are simply adjusted on the most recent available data at low energy [19]. Note that we only use data above 300 GV, given the evidence found in PAMELA data [20] of a change of slope of the spectrum of H and He below this rigidity (also confirmed by the most recent AMS data [21]; see Ref. [22] and references therein for possible interpretations of this feature). Above 300 GV, we found that an index  $x = 2.67$  provides a good fit of the data for all nuclei. In particular, TRACER [23–25] finds an index of  $x = 2.67 \pm 0.08$  for the combined elements heavier than He, while CREAM [26] finds an index of  $2.66 \pm 0.02$  protons and  $2.66 \pm 0.04$  for elements heavier than He [27]. There is admittedly some tension with the measurements of CREAM in the specific case of He nuclei [26], namely,  $x(\text{He}) = 2.58 \pm 0.02$ . However, the most recent AMS02 [21] results are in good agreement with  $x(\text{He}) = 2.67$ . Therefore, instead of leaving the spectral index free for each nucleus, we decided to stick to the most natural assumption that all nuclei have the same spectrum in rigidity and simply determine the relative abundances from the observational data. A combined fit of CREAM and AMS02 data is used to normalize the proton flux while only AMS02 is used for He nuclei, and a combined fit of CREAM, TRACER, and ATIC-2 [28] data is used for heavier nuclei.

The change of slope  $\Delta x$  (the knee) is a major feature in the GCR spectrum; its origin may be on the side of the acceleration process, for instance, a consequence of a reduction of the number of sources contributing at higher and higher energy (see Ref. [29]). Or it may be a feature of the propagation of the GCRs in the interstellar medium, through a change of the diffusion regime (e.g. Ref. [30]; see also Ref. [12] for a recent account). It could also reflect some inhomogeneity in the GCR flux, associated with the granularity and/or intermittency of the sources. In the current modelling, we do not attempt to give any interpretation of this change of slope.  $\Delta x$  is adjusted in order to obtain a good fit of the spectrum of individual nuclei (or classes of nuclei), as given by KASCADE [31,32] and KASCADE-Grande [33–36]. We find values of  $\Delta x$  between  $\sim 0.3$  and  $0.5$  coupled to values of  $E_{\text{break}}(p)$  between  $\sim 2 \times 10^{15}$  and  $4 \times 10^{15}$  eV.

Finally, the only remaining free parameter of the GCR component model is the energy scale,  $E_{\text{max}}$ , of the high-energy cutoff, which we adjust to ensure a good fit of the data in the GCR/EGCR region. In particular, values of  $E_{\text{max}}$  between  $\sim 5 \times 10^{16}$  and  $1.5 \times 10^{17}$  eV allow the heavy Galactic component to become very low to negligible at the ankle (which thus marks roughly the end of the GCR/EGCR transition [37,38]) and the combined light Galactic and extragalactic component to produce an ankle around  $\sim 10^{17}$  eV, as observed in KG data [34,35].

### III. RESULTS

In this section, we show the results obtained with the above model, after setting the values of the parameters to  $E_{\text{break}}(p) = 10^{15.5}$  eV,  $\Delta x = 0.45$  and  $E_{\text{max}} = 6 \times 10^{16}$  eV and combining the resulting Galactic component to the EGCR model using  $\alpha = 3.5$ .

The resulting spectrum is shown in Fig. 2. The left panel shows a global view of the CR *energy* spectrum above  $10^{11.5}$  eV. In particular, the assumed spectra of the four most abundant Galactic species (H, He, O, and Fe) are compared with satellite and balloon borne measurements from various experiments (CREAM [26,27], PAMELA [20], PAMELA-CALO [39], ATIC-2 [28], and TRACER [24,25]), while the total spectrum is compared below the knee with various balloon borne or ground-based experiments (RUNJOB [40], JACEE [41], ATIC-1 [42], ATIC-2 [28], and Tibet-III [43]). Taking into account the existence of some discrepancies between the various experimental results, our Galactic component is in good agreement with data for both the total spectrum and the different components below the knee energy. The right panel shows a close-up view at higher energy including the knee, the ankle, and the highest energy regions. Our model predictions are compared with KASCADE [32] as reconstructed with the QGSJetII-3 model [44], KG [35] as reconstructed with QGSJetII-4 [45] and Auger [46] data. The dashed line shows the flux obtained by summing the H and He spectra, including both GCRs and EGCRs. This is in good agreement with the KG data, when only the so-called “light” component (corresponding to electron-rich showers) is taken into account, which is intended to correspond to H and He nuclei according to the analysis presented in Refs. [34,35]. The dotted-dashed line represents the flux of all the elements heavier than Mg and is to be compared with the so-called “heavy” component. As can be seen, both components are consistent with the data and fit well within the KG systematic errors. In particular, we find that the heavy component exhibits a knee slightly below  $10^{17}$  eV, while the light component shows an ankle slightly above that energy as the light EGCR component becomes dominant over the sharply decreasing light Galactic component. The behaviors of both the heavy and light components are in very good agreement with the KG findings [33–36].

Of course, the quantitative agreement between our model and the data depends on the underlying assumption regarding the hadronic model used to reconstruct KG data. However, the choice of the hadronic model mostly influences the relative normalization of the different components. In particular, for all the hadronic models tested in Refs. [35,36], the heavy knee and light ankle features remain, and the post knee shapes of the light and heavy components remain similar to one another. Moreover, we found that the relative abundances for these components predicted by our model agree best with the data reconstructed with the QGSJetII-4 which is, to date, the most recent of the models tested against KG data and the only

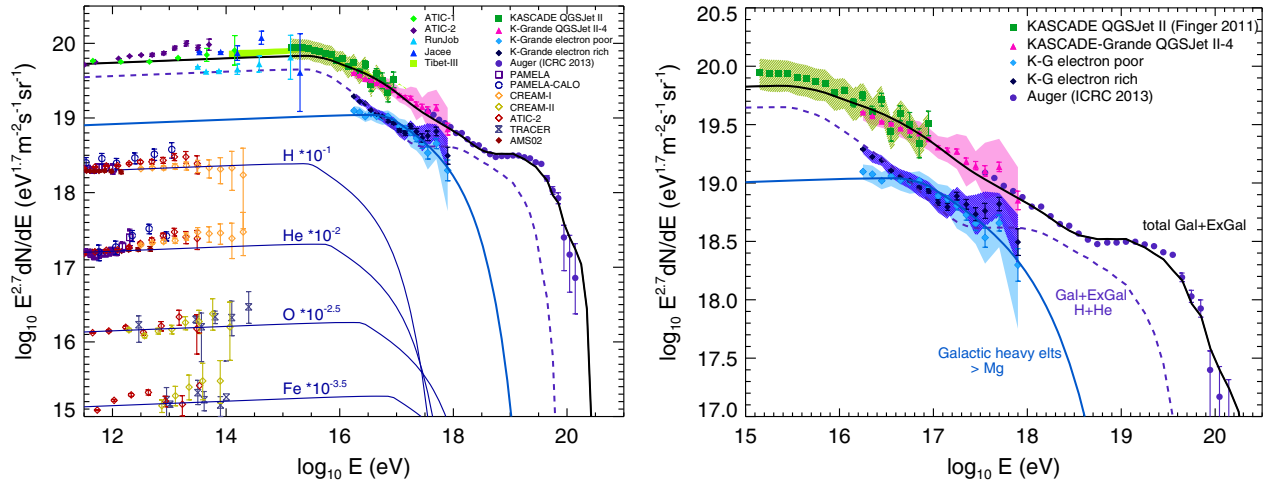


FIG. 2 (color online). Comparison between the spectrum of our global CR model and the available data, detailed in the upper right corners. The individual spectra of H, He, O, and Fe are shown for the GCR component (left, with the indicated rescaling). In addition, the heavy and light components determined by KASCADE-Grande are shown with dashed and dotted-dashed lines (see the text). Right: close-up view, showing the sum of the H and He fluxes (dashed) and the elements heavier than Mg (dotted dashed).

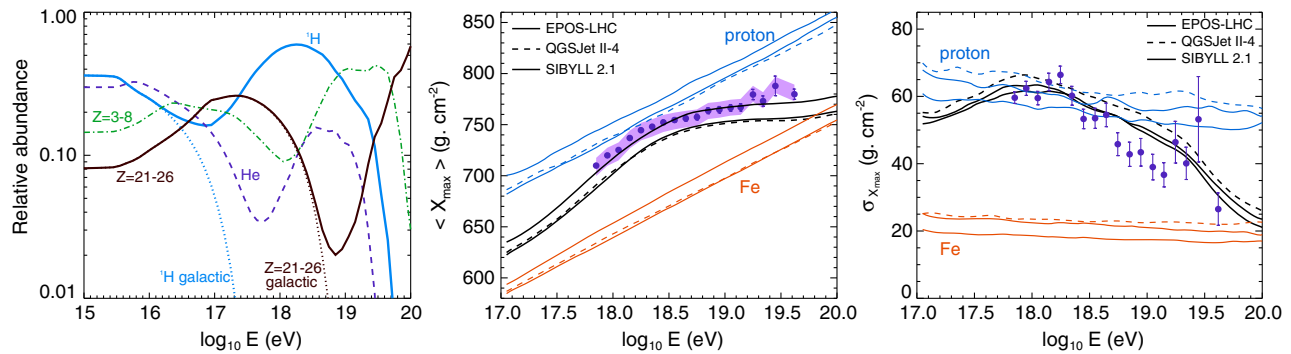


FIG. 3 (color online). Left: Relative abundance of H, He, and the elements in the indicated charge ranges, as a function of energy. Center: comparison between the model predictions for the evolution with energy of the depth of the shower maximum,  $X_{\max}$ , and the Auger data, for three different hadronic models. Right: same as the central panel, for the  $X_{\max}$  variance,  $\sigma(X_{\max})$ .

one that includes recent experimental constraints for LHC data.<sup>1</sup>

In addition to these spectral features, our model provides a detailed description of the CR composition from the knee to the highest energies, which allows a comparison with the data. The left panel of Fig. 3 shows the relative abundance of H, He, and the following two dominant sets of nuclei, namely, CNO (and sub-CNO) nuclei and sub-Fe (and Fe) nuclei. For protons and sub-Fe nuclei, we also show separately the Galactic component, using dotted lines.

As can be seen, even though the Galactic protons essentially disappear at  $\sim 1.5 \cdot 10^{17}$  eV, the abundance of protons never drops below 15% and rises up again to more than 50% (with a maximum around 60%) just above  $5 \cdot 10^{17}$  eV. The fact that these protons, which ensure a

dominantly light component across the ankle, are extragalactic protons is fully consistent with the anisotropy measurement of Auger. Indeed, a Galactic component of protons would most probably produce a significant anisotropy toward the Galactic center and/or plane, which is excluded by the data. Finally, the proton fraction is seen to rapidly decrease above the ankle, to finally vanish above a few  $10^{19}$  eV, letting heavier and heavier nuclei dominate the UHECR spectrum.

The behavior of Fe (and sub-Fe) nuclei is quite different, as there is practically no overlap between the Galactic component, which ends at a few  $10^{18}$  eV (i.e., 26 times higher in energy than the Galactic protons), and the extragalactic component, which rises up strongly above  $10^{19}$  eV, to reach 60% at  $10^{20}$  eV.

Finally, between  $\sim 6 \cdot 10^{18}$  and  $\sim 5 \cdot 10^{19}$  eV, the composition is dominated by CNO elements.

It is possible to compare the data with the model predictions for the composition-dependent observables, namely, the depth of the maximum shower development,

<sup>1</sup>Analyses using the EPOS-LHC [47,48] model are not available yet. We note, however, that the predictions of QGSJetII-4 and EPOS-LHC in terms of KG composition sensitive observables are quite similar.

traditionally referred to as  $X_{\max}$ , and its spread at a given energy,  $\sigma(X_{\max})$ . This is done in Fig. 3, where we plotted the evolution of these two observables with energy, together with the Auger data. For this, we simulated the development of a large number of cosmic ray showers for the different nuclei and energies, using the CONEX shower simulator [49] with three different choices of the hadronic interaction model (SIBYLL2.1 [50], QGSJetII-4 [45], and EPOS-LHC [47,48]). The agreement between the prediction of our model and the data is remarkable over the entire energy range, both qualitatively and quantitatively, especially when the shower development is calculated using the EPOS-LHC hadronic model. It is again interesting to note that this model takes into account the recent constraints from measurements performed at the LHC. Although they probably do not reproduce perfectly all air showers properties [51], the most recent hadronic models seem to give a more coherent picture of the evolution of the composition deduced from indirect measurements, from the knee to the highest energies.

When reconstructed using the EPOS-LHC model, the Auger data indicate a global trend of the evolution of the abundances in good agreement with our predictions. In particular, the dominant class of nuclei around  $10^{19}$  eV would be CNO [15]. However, if the QGSJET II-4 and SIBYLL2.1 models are used, the Auger data would favor a dominant contribution of He up to  $3 \cdot 10^{19}$  eV, i.e., above the GZK cutoff energy for He nuclei. The latter trend, if validated by the next generation of hadronic models, would be challenging for any extragalactic model (unless nonstandard assumptions are made, e.g., the presence of a strong nearby source). We note, however, that the difference between the two different interpretations is mostly due to a consistent difference of  $\sim 15$  g/cm<sup>2</sup> in the average  $X_{\max}$  value predicted by the different hadronic models (as also seen in Fig. 3, center) which inevitably leads to uncertainties when comparing the data with model predictions. Future constraints, notably from CERN experiments, should help further improving the convergence between the various hadronic models.

#### IV. SUMMARY

We showed that the whole CR spectrum, including the key region of the GCR/EGCR transition, can be described by simply superposing a rigidity-dependent GCR component and a generic EGCR model, without additional degrees of freedom.

In our model, the GCR component is identical for all nuclei with the same rigidity. The maximum energy of protons accelerated in Galactic sources is  $\sim 6 \cdot 10^{16}$  eV, and the transition toward extragalactic protons takes place around  $10^{17}$  eV, where KASCADE-Grande observes an ankle in the light CR component. While the kneelike break in the GCR proton component occurs at  $\sim 3 \cdot 10^{15}$  eV, the corresponding break in the Fe components appears at  $\sim 8 \cdot 10^{16}$  eV, which is in agreement with the observed “heavy knee” in the KASCADE-Grande data. The normalizations of the light

and heavy components are also in good agreement with the data.

Our results suggest that extragalactic protons account for more than 50% of the total flux from  $\sim 5 \cdot 10^{17}$  to  $\sim 5 \cdot 10^{18}$  eV and drop below 10% above  $3 \cdot 10^{19}$  eV. The dominant class of nuclei between  $\sim 6 \cdot 10^{18}$  and  $\sim 5 \cdot 10^{19}$  eV is CNO. The evolution of the composition predicted by our model has been shown to be fully compatible with the Auger data [14,15], across the observed transition from a light-dominated to a heavy-dominated composition.

An important reason for the model success is that the EGCR source spectrum is significantly steeper for protons than for the heavier nuclei. This is because most of the EGCR protons are in fact decay products of freely escaping secondary neutrons, produced during the acceleration through the photo-dissociation of heavier nuclei. While this is a direct consequence of our acceleration model detailed in Ref. [13], it should not be taken as an argument in favor of the GRB source model. We believe that a softer proton component is a generic feature of UHECR acceleration occurring in photon-rich environments. Combined with a relatively low maximum proton energy, a single EGCR component can thus explain in a consistent way the evolution of the composition above  $10^{18}$  eV as well as the spectral and composition features observed below the ankle, down to the knee. In particular, the relative energy scale between the “light ankle” and the ankle [a factor  $\sim 30 \sim Z(\text{Fe})/Z(\text{p})$ ] is most naturally explained within this framework involving a transition between two components.

We thus conclude that, unless new data will contradict the current observational status, there is no need for invoking any additional CR component. Now, if one opts indeed for the minimal assumption that a single component accounts for all GCRs, then our results strongly suggest that this component should be able to accelerate protons up to at least  $\sim 5\text{--}6 \cdot 10^{16}$  eV. This might be in tension with the generally accepted models for particle acceleration at the shocks of individual supernova remnants in the Galaxy, which hardly reach energies much larger than  $10^{15}$  eV. This could suggest that these models should be modified or that other classes of sources may have a dominant contribution to the GCRs, perhaps through collective acceleration processes as might be expected in superbubbles (see, e.g., Ref. [52] and references therein).

Our model and more generally the phenomenology of the GCR/EGCR transition should be further constrained by new experiments, such as IceTop [53,54] and the low-energy extensions of Auger and TA [55,56] which should bring new high statistics and high resolution data from the knee to the ankle in the years to come.

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