PROCEEDINGS OF SCIENCE

Transition from Galactic to extragalactic cosmic-rays : implications for the highest energy Galactic cosmic-rays

Denis Allard*
Laboratoire Laboratoire Astroparticules et Cosmologie (APC), Université Paris 7/CNRS, 10 rue A. Domon et L. Duquet, 75205 Paris Cedex 13, France.
E-mail: denis.allard@apc.univ-paris7.fr

In this contribution, we discuss the transition from galactic to extragalactic cosmic-rays and its implications for the highest energy galactic cosmic-rays. We first review the aspects of extragalactic ultra-high-energy cosmic-ray propagation relevant to the phenomenology of the transition and present different possible interpretations for the "ankle" of the cosmic-ray spectrum. We then discuss the implications of recent cosmic-ray composition related measurements from the Pierre Auger observatory and the KASCADE-Grande experiment. We argue that the interpretation of the ankle as the signature of the transition from galactic to extragalactic cosmic-rays is currently favored by the analyses released by both experiments. We briefly discuss the implications for galactic cosmic-ray sources as well as the forthcoming experiments which should definitely reveal the origin of the ankle of the cosmic-ray spectrum.

Cosmic Rays and the InterStellar Medium - CRISM 2014,
24-27 June 2014
Montpellier, France

*Speaker.

PoS(CRISM2014)012

1. Introduction

Despite its remarkable regularity over more than 12 orders of magnitude in energy, the cosmic-ray (CR) spectrum exhibits a few features that are subject to intense observational and theoretical studies, as they may provide valuable informations to eventually understand the origin of both galactic (GCRs) and extragalactic (EGCRs) cosmic-rays. The so-called knee of the CR spectrum is visible around $3-4\times10^{15}$ eV. This feature seems to be caused by a significant inflection of the light cosmic-ray component[1]. Popular explanations for this feature involve either an inflection in the spectrum of galactic cosmic-ray source(i.e, that the maximum acceleration energy of protons at the sources has been reached) or a change (steepening) of the energy evolution of the cosmic-ray protons confinement time in the Galaxy (see for instance [2] for a review or [3] for a recent study). Very soon after the experimental discovery of the knee, it was suggested that knees of the different individual elements with charge Z should occur at energies $E_{\rm knee}(Z) = Z\times E_{\rm knee}^{\rm proton}$ [4], resulting in a relatively smooth all particle spectrum above the knee and a cosmic-ray composition becoming gradually heavier with the energy. Such a composition trend is indeed observed by most cosmic-ray observatories at least up to $\sim 10^{17}$ eV (see [5] for a review). The energy range between 10^{17} and 10^{19} eV is of particular interest since it is believed to host the transition from GCRs to EGCRs. Such a transition must indeed occur as it is established (notably from observations of galactic gamma-rays due to π^0 CR interactions) that the low-energy CRs have a galactic origin, while simple considerations about the confinement of particles in the Galaxy and the galactic halo strongly suggest that most of the highest-energy CRs must have an extragalactic origin.

The most natural shape that a transition between two steady (featureless) components may take a priori is that of an "ankle", i.e., a hardening of the spectrum, where the harder, initially sub-dominant component at low energy simply takes over from the softer component at some transition energy, $E_{\rm t}$. Interestingly, an ankle is indeed observed in the CR spectrum, around $3-4\times10^{18}$ eV, roughly in the energy range where the confining effect of the galactic magnetic fields is expected to lose its efficiency and the GCR component is thus expected to die out. It is thus tempting to interpret the observed ankle as a natural signature of the GCR/EGCR transition (e.g., [6]) and the knee, located at an energy roughly three order of magnitude lower, as the very starting point of the transition process with the steeping of the light galactic component.

Such a scenario would of course have some strong implications for galactic cosmic-ray sources since it requires the heavy galactic cosmic-ray component to extend at least up to the ankle energy and as a result the galactic proton component to energies of the order of 10^{17} eV (one and a half order of magnitude in energy above its knee) which may appear quite challenging for some galactic cosmic-ray source candidates such as supernova remnants (SNRs).

An interesting way to understand the transition from GCR to EGCR and to obtain constraints about the highest energy GCR can be provided by the study of the highest-energy end of the CR spectrum, where cosmic-rays most likely have an extragalactic origin. In particular, the study of the propagation of extragalactic ultra-high-energy cosmic rays (UHECRs) can provide important hints on the possible ways (typical energy range, observational spectral and composition signatures) the GCR to EGCR transition may occurs.

In this contribution, we review the aspects of extragalactic UHECR propagation relevant to the phenomenology of the transition for GCR to EGCR, we discuss the different transition models and their distinctive observational signature. We then argue, in the light of recent composition analyses released by KASCADE-Grande (in the $10^{16}-10^{18}$ eV energy range) [7, 8] and the Pierre Auger observatory (above 10^{18} eV) [9, 10], that the interpretation of the ankle as a signature of the transition from GCR to EGCR, and as a consequence smooth individual knees for the different elements of galactic cosmic-rays, are currently favored.

2. Propagation of extragalactic UHECRs

One of the most important aspects of the extragalactic propagation of UHECRs[1] is the modeling of their energy and mass losses due to interactions. In the extragalactic medium, except maybe in the immediate vicinity of the UHECRs accelerators, only photon backgrounds are relevant. Besides the cosmic microwave background (CMB) photons which represent the densest photon background, protons and nuclei interact mainly with infrared, optical and ultra-violet photons (hereafter IR/Opt/UV photons). In the past years, the models of IR/Opt/UV density and their cosmological evolution have been better constrained by multiwavelength observations.

2.1 Interactions of protons and nuclei

Besides the adiabatic expansion losses, UHECR protons mainly suffer from the pair production mechanism which energy threshold with CMB photons is around 10^{18} eV and the pion production which is extremely efficient above $\sim 7\times10^{19}$ eV. The relevance of these energy loss mechanisms for the propagation of UHECR protons was pointed out very early after the discovery of the CMB photons. Greisen [11] and independently Zatsepin and Kuzmin [12] estimated the opacity of the universe for cosmic-ray protons above 10^{20} eV due to the pion production mechanism and predicted the existence of the so-called GZK cut-off.

The energy evolution of UHECR protons loss length $\chi_{\rm loss}(\rm E)$ is represented in Fig. 1a. The contribution of the different loss processes and the different photon backgrounds can be seen. The contribution of the IR/Opt/UV for pair production and pion production interaction is almost irrelevant on the whole energy range. At low energy, energy losses are dominated by the contribution of the universal expansion up to a few 10^{18} eV, the pair production mechanism starts to dominate just above its energy threshold. Finally, the pion production mechanism takes over above $\sim 7\times10^{19}$ eV. Above 10^{20} eV the loss length drops to very low values and the large scale universe becomes opaque to cosmic-rays as pointed out in the original papers predicting the existence of the GZK cut-off. As we discuss later, this energy evolution of $\chi_{\rm loss}$ is unique to protons and has extremely interesting consequences on the expected shape of the diffuse spectrum produced by a cosmological distribution of sources.

The interactions experienced by nuclei[2] with photon backgrounds are different from the proton case. The most complete discussion of these interaction processes can be found [13]. Unlike the proton case, one has to distinguish two categories of energy loss processes, those triggering a decrease of the nucleus Lorentz factor and those leading to its photodisintegration. In the first category, nuclei propagation is mainly affected by the adiabatic expansion and the pair production

[1] Many more details and references (omitted to respect the format of the proceedings) can be found in [14]

[2] When using the term "nucleus" we exclude the case of single nucleons.

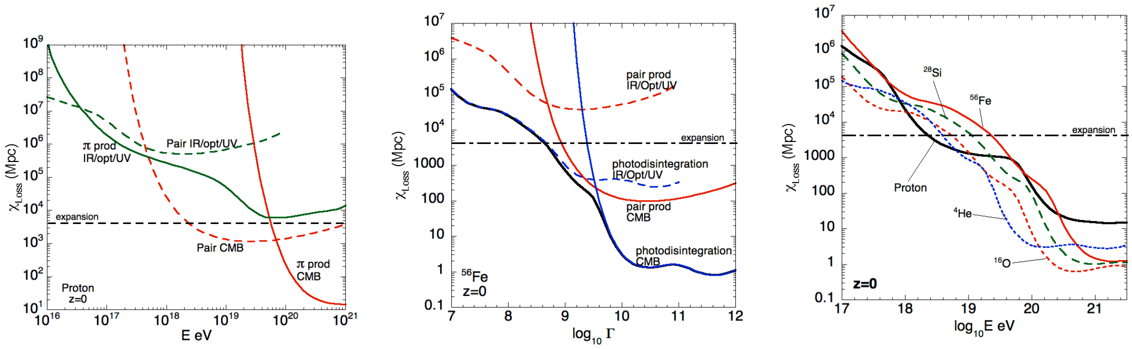

Figure 1: Left : Energy evolution of the energy loss length $\chi_{\rm loss}$ of protons, the contributions of different energy loss processes (adiabatic expansion, pair production and pion production) are displayed, as well as the different photon backgrounds (see labels).Center: evolution of the attenuation length of iron as a function of the Lorentz factor at z = 0. The contribution of pair production and photodisintegration processes off the CMB and IR/Opt/UV photons are separated. Right: comparison of the energy evolution of the attenuation length of different nuclei at z = 0.

mechanism. For the latter, the energy threshold is proportional to the mass A (in the laboratory frame, for a given photon spectral energy distribution) of the parent nucleus whereas the loss length decrease like $\sim A/Z^2$ at a given Lorentz factor [13].

Concerning photodisintegration, different processes become dominant at different energies. The lowest energy and highest cross section process is the giant dipole resonance (GDR). The GDR is a collective excitation of the nucleus [15] in response to electromagnetic radiation between ∼10 and 50 MeV [3] where a strong resonance can be seen in the photoabsorption cross section. The GDR triggers mostly the emission of one nucleon (most of the time a neutron but it depends on the structure of the parent nucleus, α emission can also be strong for some nuclei), 2, 3 and 4 nucleon channels can also contribute significantly though their energy threshold is higher. Above $\sim 40-50$ MeV in the nucleus rest frame, the Quasi-deuteron (QD) and then the baryonic resonances (pion production), which are multi-nucleon emission processes successively take over. Fig. 1b shows the contribution of pair production and photodisintegration processes to the total attenuation length of iron nuclei. Above $\Gamma \sim 10^{8.8}$ photodisintegration processes take over and dominate the energy losses over the whole energy range. A comparison between the attenuation lengths of different species is displayed in Fig .1c. The difference in the shape of the evolution of $\chi_{\rm loss}$ between the proton and complex nuclei cases is clearly visible (we will discuss the consequences in the next section). For complex nuclei, two sharp drops are visible in the energy evolution of $\chi_{\rm loss}$, taking place at energies more or less proportional to the mass of the parent nucleus[4]. The first one (around $\sim A \times 10^{18}$ eV at z=0) is due to combined effect of (mainly) photodisintegration on far-infrared photons and pair production on CMB photons and the second (even sharper, around $\sim A \times 4\,10^{18}$ eV at z=0) to photodisintegration on CMB photons. These features in the loss length are of course expected to be seen in the propagated spectra (see below) for the different elemental

[3]The threshold for most nuclei is between 10 and 20 MeV except for peculiar cases like ^{9}Be or the dinucleon and trinucleon

[4]This is due to the fact the photon energy thresholds for GDR interactions are similar for most species as mentioned above.

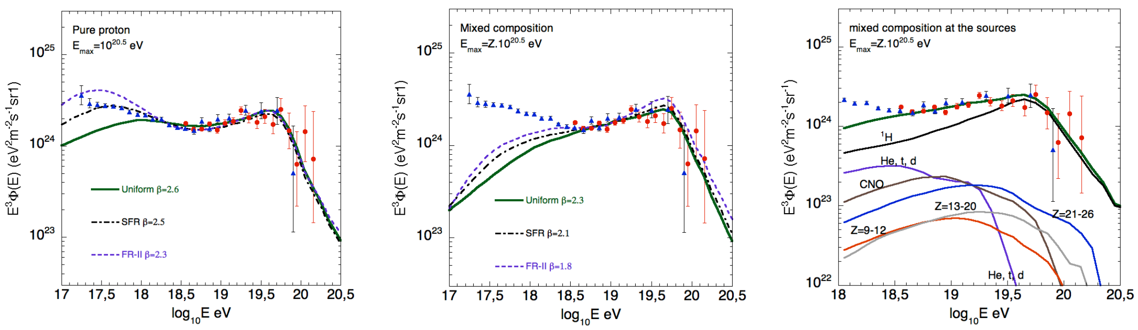

Figure 2: Left: Propagated spectra assuming a pure proton composition at the extragalactic sources for different hypotheses on the cosmological evolution of the cosmic-ray luminosity (see legend), the maximum energy at the sources is $E_{max} = 10^{20.5}$ eV. The spectra are compared with HiRes monocular data. Center: Same as left panel but assuming a mixed composition at the sources similar to low energy galactic cosmic-rays, the maximum energy of the different elements scales proportionally with the charge : $E_{max}(Z) = Z \times 10^{20.5}$ eV. Right : Same as the central panel, here the contributions of different elemental groups are shown (for the "uniform" evolution case only).

groups.

2.2 Propagated spectra and evolution of the composition

Once the energies losses of UHECR proton and nuclei are characterized one can in principle calculate propagated spectra by assuming a cosmological distribution of UHECR sources, the evolution of their luminosity with the redshift as well as the their injection spectra and composition. The sources are most of the time assumed to be standard candles (e.g, same luminosity at a given redshift, same composition and injection spectral index and same maximum injection energy or rigidity), for the sake of simplicity (see discussion in [14]). For the cases we consider in next two paragraphs, we assume the maximum energy at the source $E_{max}(Z) = Z \times 10^{20.5}$ eV.

2.2.1 pure proton case

We start our discussion by assuming a pure proton composition at the extragalactic sources. Fig. 2a shows propagated spectra assuming different cosmological evolution for the cosmic-ray luminosity (namely, no evolution labeled as "uniform", star formation rate (SFR) evolution and an evolution similar to that of strong radio AGN, hereafter labeled as FR-II) adjusted to HiRes monocular spectra [16]. The features that can be seen seen in the spectrum are a direct translation of the χ_{loss} evolution discussed in the previous section : at low energy, energy losses are dominated by the adiabatic expansion (independent of the energy) and the spectrum more or less keeps the "injected shape". Above the pair production threshold χ_{loss} decreases quite abruptly with the energy which triggers a steepening (softening) of the propagated spectra. Well above the pair production threshold, the evolution of χ_{loss} flattens and which results in a hardening or the spectrum (the sequence is called the "pair production dip"). Above the pion production production threshold, χ_{loss} decreases again abruptly to reach very low values and the propagated spectrum shows a very steep softening which is the so-called GZK cut-off for protons.

One of the remarkable characteristics of the pure proton case is to be able to reproduce the ankle of the cosmic-ray spectrum with the sole extragalactic component. This observed spectral feature is in this case associated with the energy losses of extragalactic protons and not with the transition from galactic to extragalactic cosmic-ray (hereafter GCR to EGCR transition) as proposed in most models. The "pair production dip" [17] as an astrophysical interpretation for the ankle has very important implications for galactic cosmic-ray sources : since the transition for GCR to EGCR potentially ends between $\sim 3 \times 10^{17}$ and 10^{18} eV (depending on the cosmological evolution assumed), galactic sources are not required to accelerate proton to energies significantly larger than a few 10^{16} eV (see Fig. 3a). In this framework, the knees of the different elements are sharp and the GCR to EGCR happens very fast but without leaving any strong signature in the all particle spectrum which might look quite unnatural.

2.2.2 mixed and nuclei dominated compositions

One of the consequences of adding nuclei in UHECR sources composition is to impact the prediction of the presence of a pair production dip. Indeed as mentioned in the previous sections, the pair production dip is a signature of extragalactic proton energy losses and is then "encoded" in the energy evolution of the loss length. As the energy losses of nuclei and their energy evolution are different from the proton case, one does not expect such a feature in their propagated spectra. One can show that the possibility of observing a pair production dip in the extragalactic cosmic-ray spectrum requires the abundance of complex nuclei at the source to be less than $\sim 10\%$ (depending on the mixture of complex nuclei assumed) [17, 18].

As a case study, we consider the case of a mixed composition equivalent to that of low energy galactic cosmic-rays as a possible composition for extragalactic sources. The propagated spectra for this mixed composition, compared to the monocular spectra from HiRes are represented in Fig. 2b. As discussed earlier, the presence of a pair production dip is not expected in this case and the experimental spectrum can only be reproduced above the ankle with the extragalactic component (this remains true if even if the source composition is dominated by nuclei) which is in this case the signature of the end of the GCR to EGCR transition. Concerning the energy evolution of the composition of the extragalactic component above the ankle, the contribution the different elemental groups is displayed on Fig. 2c, for the "uniform" evolution case. The proton component obviously presents the same features as described above. For nuclei, the behavior of the elemental spectra can also be easily understood from the energy evolution of $\chi_{\rm loss}$. The different groups show a catastrophic drop above $\sim \mathrm{A} \times 5\,10^{18}$ eV due to photodisintegration with CMB photons thus the contribution light and intermediate nuclei should be the first to disappear above their interaction threshold with CMB photons. At 10^{20} eV for instance, besides protons, only nuclei heavier than $\sim$ Si should significantly contribute. Overall the composition is expected to get lighter above $\sim 10^{19}$ eV if all the species are accelerated above 10^{20} eV.

From the point of view of the GCR to EGCR transition, the mixed composition case has thus different implications for galactic cosmic-ray sources : the heavy (Fe) galactic component is required to reach at least the ankle (see Fig. 3a) and as a consequence the proton component to reach $\sim 10^{17}$ eV implying smooth individual knees for the different elements of GCR.

Although they appear to be degenerated from the point of view of the spectrum, the dip and the ankle transition model imply very different prescriptions for the evolution of the composition above

PoS(CRISM2014)012

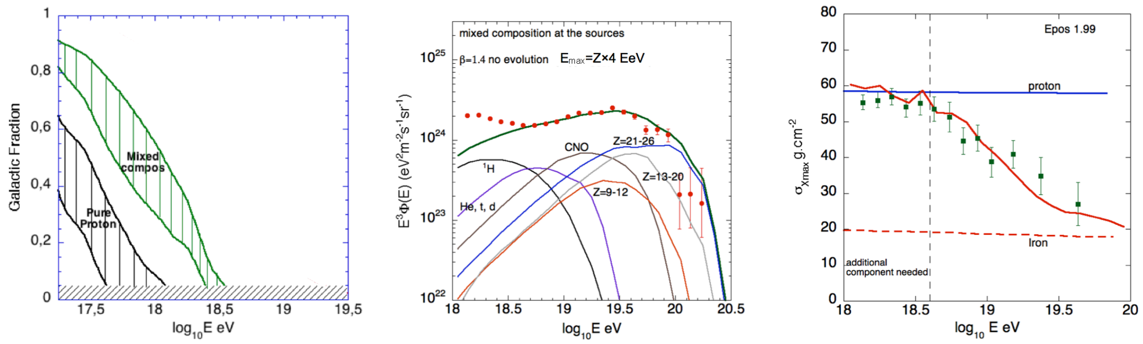

Figure 3: Left: Energy evolution of the contribution of the galactic component obtained by substracting the extragalactic spectral shown in Fig. 2 to the experimental spectrum. The galactic fractions inferred for the "dip" and mixed composition models (for different cosmological evolutions of the sources) are shown (from [19]. Center: Propagated spectrum assuming the same mixed composition as in Fig. 2b, the maximum energy at the sources is $E_{\max}(Z) = Z \times 4\,10^{18}$ eV and the spectral index $\beta = 1.4$. Right : Energy evolution of $\sigma_{X_{\max}}$, resulting from the evolution of the composition shown in the central panel, compared to Auger data.

the knee. Composition related measurements from the Pierre Auger observatory and KASCADE-Grande recently allowed to estimate the evolution of the composition in a wide energy range of interest for the GCR to EGCR transition and gave key constraints for the above mentioned transition models.

3. Constraints from Auger and KASCADE-Grande composition analyses

The Pierre Auger collaboration, recently provided the largest statistics composition analyses above $\sim 10^{18}$ eV, based on the measurement of the mean maximum depth of shower development ($\langle X_{\max} \rangle$) and its associated dispersion [9, 10]. When compared with air shower simulations, the energy evolution of $\langle X_{\max} \rangle$ and its dispersion (hereafter RMS) strongly suggest that the composition, light at the ankle, is evoluting toward heavier elements as the energy increases. This trend is especially striking on the evolution of the RMS that becomes very narrow and close to what is expected for heavy dominated compositions (very a low abundance of protons) in the last energy bins around $10^{19.5}$ eV. This trend, if indeed due to a change in of composition of UHECRs, has extremely important implications. First, it rules out most astrophysical models that predicted a proton dominated composition at the highest energies, and in particular the interpretation of the ankle as being the pair production dip. The proton dominated mixed composition (see above) proposed in [18] and predicting a composition going to lighter elements with increasing energy is also totally incompatible with this trend. As mentioned in the previous paragraph such an evolution of the composition is not expected if the different species present in the source composition are accelerated above 10^{20} eV per nucleon in which case the composition would be expected to become lighter even for heavy dominated compositions at the sources. The most likely explanation for the opposite trend suggested by Auger data would be to assume that the UHECR sources (or at least most of them) are not able to accelerate protons to the highest energies but can provide nuclei with higher energy with the charge scaling of the maximum energy expected in confinement limited acceleration processes. As an illustrative example, keeping, the source composition identical (at a given energy) to the above mentioned mixed composition case and assuming a maximum energy at the source $E_{max}(Z) = Z \times 4\,10^{18}$ eV, one has to consider much harder source spectral indexes $\beta = 1.4$ to reproduce the spectrum measured by Auger [20], as show in Fig. 3b. The associated evolution of the composition above the ankle can be translated into the expected evolution the mean maximum depth of shower development ($\langle X_{max} \rangle$) and its associated dispersion ($\sigma_{X_{max}}$) using air shower simulations. The expected evolution of $\sigma_{X_{max}}$[5] associated to the spectrum displayed in Fig. 3b, is shown in Fig. 3c and compared to the Auger measurement reported in [9]. One can see that the evolution of $\sigma_{X_{max}}$ is quite well reproduced by the model, lending some weight to the above interpretation of the evolution of the composition suggested by Auger data.

From the point of view of the GCR to EGCR transition and galactic cosmic-ray sources, the "low E_{max} model" we briefly introduced has similar implications as those discussed in Sect. 2.2.2, and requires smooth knees for the different elements of galactic cosmic-rays (see above).

Recent composition analyses from the KASCADE-Grande experiment have recently allowed to constrain the evolution of the composition in the energy range from $\sim 10^{16}$ to $\sim 10^{18}$ eV which is key for the understanding of the GCR to EGCR transition. Indeed, the KASCADE-Grande collaboration released two successive composition analyses [7, 8] showing :
(*i*) a knee-like structure in the spectrum of the heavy component of cosmic rays, with a break located slightly below 10^{17} eV. This feature is compatible with the presence of a "Fe-knee" located at an energy ~ 26 times larger than the proton-knee at $\sim 3-4\,10^{15}$ eV.
(*ii*) an ankle-like feature in the energy spectrum of light elements of cosmic rays with a break located at $\sim 10^{17}$ eV.
(*iii*) a slope of the light component fitted below the ankle-like break compatible with the slope of the heavy component fitted above the "Fe-knee".
Put together, these observations point toward a rather natural picture. The ankle-like break in the light CR spectrum at $\sim 10^{17}$ eV [8] implies that the light Galactic component (and then probably the proton component) extends at least up to this energy. It further implies that the heavy Galactic component (at least the Fe component) should extend at least up to $\sim 3\,10^{18}$ eV, which is very close to the ankle energy. This point is further supported by the fact that the post "Fe-knee" heavy component (which again has a spectral slope compatible with that of the pre-ankle light component) does not show any evidence for a cut-off in the whole energy range covered by KASCADE-Grande, which extends up to 10^{18} eV [7]. These two composition analyses thus make a strong case in favor of smooth, rather than sharp, individual knees for the different components of GCRs. An extra-galactic component such as that predicted by mixed composition models would fit rather well in this picture, emerging around 10^{17} eV (where it represents a few percents of the total spectrum), completely dominating the Galactic component at the ankle with a composition still dominated by light nuclei, and getting progressively heavier as the energy increases. Although, the simple example given in Fig. 3b might imply a transition which is slightly too steep (due to the very hard source spectral index used to fit the data) to fit both Auger and KASCADE-Grande composition data, more elaborated source models (taking into account photodisintegration at the sources, see the discussion in [21]) are able to give more consistent results on the whole energy range.

[5] using the EPOS 1.99 hadronic model but it is important to note that unlike $\langle X_{max} \rangle$ the predictions of $\sigma_{X_{max}}$ do not strongly depend on the hadronic model used.

Although the above picture looks quite natural and consistent, let us not for forget that a full study of the hadronic model dependence of the features claimed by the KASCADE-Grande experiment is still needed. Moreover, the current overlap between the energy ranges covered by the KASCADE-Grande and Auger experiments is very small. This situation should however improve significantly in the next few years since the low energy extensions of Auger [22] and TA (TALE, [23]) are expected to increase the energy range covered by both experiments down to $\sim 10^{17}$ eV (and even below in the case of TALE), then fully covering the energy range where the GCR-to-EGCR transition is expected to take place.

It is important to note that the trends suggested by KASCADE-Grande (namely being consistent with the light galactic component extending up to at least $\sim 10^{17}$ eV and the heavy component to the ankle) which appear quite consistent with Auger data at higher energy, have strong potential implications for galactic cosmic-ray sources. Although models based on magnetic field shock amplification may allow SNRs to accelerate cosmic-ray protons to very high energies during the first few years of the shock expansion (see for instance [24] and references therein), it is not clear at all that supernova remnants can provide enough power in cosmic-ray above the knee energy to fit cosmic-ray data as argued in [25]. Again, higher statistics and resolution cosmic-ray measurements in this energy range as well as future $\gamma - ray$ constraints [26] of galactic cosmic-ray source candidates should bring crucial constraints on the origin of galactic cosmic-rays in the next few years.

Acknoledgements

I wish to thank Nicolas Busca, Guillaume Decerprit, Noémie Globus, Elias Khan, Angela Olinto and especially Etienne Parizot for their collaboration on studies related to this contribution. I also thank Alexandre Marcowith and the organizers of the CRISM2014 workshop for their kind invitation and their helpful availability during the conference.

References

[1] Antoni T. et al., [KASCADE collaboration], 2005, Astropart. Phys., 24, 1, astro-ph/0505413

[2] Hörandel J. R., 2004, Astropart. Phys. 21 241-265. arXiv: astro- ph/0402356.

[3] Giacinti G., Kachelriess M. & Semikoz D. V., 2014, ArXiv e-prints arXiv:1403.3380.

[4] Peters B., 1961, Il Nuovo Cimento 22 800

[5] Kampert K. H. & Unger M., 2012, Astropart. Phys., 660-678

[6] Nagano N., et al., 1992, Nucl. Part. Phys. 18 423

[7] Apel W. D. et al. [KASCADE-Grande collaboration], 2011, Phys. Rev. Lett., 107, 171104

[8] Apel W. D. et al. [KASCADE-Grande collaboration], 2013, Phys. Rev. D, 87, 081101

[9] Abraham J. et al. [Pierre Auger Collaboration], 2010, Phys. Rev. Let., vol. 104 pp. 91101

[10] Aab A. et al. [the Pierre Auger collaboration], 2013, proceedings of the 33rd International Cosmic-Ray Conference, Rio (Brasil), arXiv:1307.5059

[11] Greisen K., 1966, PRL 16 748

[12] Zatsepin G. T. and Kuzmin V. A., 1966, Sov. Phys. JETP Lett. 4 78

[13] Rachen J. P., 1996, Interaction processes and statistical properties of the propagation of cosmic-rays in photon backgrounds, Ph.D. Thesis, Bonn University

[14] Allard D., 2012, Astropart. Phys. 39, 33-43

[15] Khan E., Goriely S., Allard D., Parizot E., Suomijarvi T., Koning A. J., Hilaire S., Duijvestijn M. C., 2005, Astroparticle Physics, 2005 vol. 23 pp. 191

[16] Sokolsky P. and Thomson G. B., 2007, Journal of Physics G: Nuclear and Particle Physics vol. 34, pp. 401

[17] Berezinsky V. S., Gazizov A. Z., Grigorieva S.I., Phys. Rev. D., 74, 04300

[18] Allard D., Parizot E., Olinto A. V., Khan E., Goriely S., 2005, A&A, 443, L29

[19] Allard D., Parizot E., Olinto A. V., 2007, A&A, 473, 59

[20] Abraham J. et al. [Pierre Auger Collaboration], 2010, Physics Letters B, vol. 685 pp. 239

[21] Globus N., Allard D., Mochkovitch R., Parizot, E., 2014, ArXiv e-prints arXiv:1409.1271, submitted to MNRAS

[22] Abreu P. et al. [Pierre Auger Collaboration], 2011, proc. of the 32nd international cosmic-ray conference, Beijing (China), arXiv:1107.4807

[23] Sagawa H. et al. [Telescope Array Collaboration], 2009, proc. of the 31st international cosmic-ray conference, Lodz (Poland). www.telescopearray.org

[24] Bell A. R., Schure K. M., Reville B., Giacinti G., 2013, MNRAS 431 415

[25] Parizot E., 2014, ArXiv e-prints arXiv:1410.2655,

[26] The CTA consortium, 2010, arXiv:1008.3703