



## Astrophysics Motivation behind the Pierre Auger Southern Observatory Enhancements

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**Abstract:** The Pierre Auger Collaboration intends to extend the energy range of its southern observatory in Argentina for high quality data from 0.1 to 3 EeV. The extensions, described in accompanying papers, include three additional fluorescence telescopes with a more elevated field of view (HEAT) and a nested surface array with 750 and 433 m spacing respectively and additional muon detection capabilities (AMIGA). The enhancement of the detector will allow measurement of cosmic rays, using the same techniques, from below the second knee up to the highest energies observed. The evolution of the spectrum through the second knee and ankle, and corresponding predicted changes in composition, are crucial to the understanding of the end of Galactic confinement and the effects of propagation on the lower energy portion of the extragalactic flux. The latter is strongly related to the cosmological distribution of sources and to the composition of the injected spectrum. We discuss the science motivation behind these enhancements as well as the impact of combined HEAT and AMIGA information on the assessment of shower simulations and reconstruction techniques.

### Target energy interval

The Southern site of the Pierre Auger Observatory, which will be completed in its original design during the next few months, has an energy threshold of  $\sim 3^{18}$  eV and  $\lesssim 10^{18}$  eV for surface and fluorescence events respectively. Two enhancements, AMIGA and HEAT [1, 2], are already planned in order to extend its energy threshold for high quality data down to  $10^{17}$  eV.

The baseline design of Auger is optimized for energies corresponding to the middle of the ankle and upwards to the highest energies. The enhancements, on the other hand, have as a prime objective to lower the energy threshold of the detector down to  $10^{17.0}$  eV (see, figure 1). Such extension will allow the complete inclusion of the ankle and the second knee inside the observation range of Auger. This would also have the additional advantage of adding an overlap with KASCADE Grande [4] which is of fundamental importance in order to validate results.

The second knee has been observed in the vicinity of  $4 \times 10^{17}$  eV by Akeno [5], Fly's Eye stereo [6], Yakutsk [7] and HiRes [8]. The physical interpretation of this spectral feature is uncertain at present. It may be either the end of the Galactic cosmic ray component, the pile-up from pair creation processes due to proton interactions with the cosmic microwave background radiation during propagation in the intergalactic medium or a combination of both effects.

The ankle, on the other hand, is a broader feature that has been observed by Fly's Eye [6] around  $3 \times 10^{18}$  eV as well as by Haverah Park [10] at approximately the same energy. These results have been confirmed by Yakutsk [7], HiRes [8] and Auger in hybrid mode [9]. AGASA also observed the ankle, but they locate it at a higher energy, around  $10^{19}$  eV [11]. Several physical interpretations are possible which are intimately related with the nature of the second knee. The ankle may be the transition point between the Galactic and extragalactic components or the result of pair creation by protons in the cosmic microwave background.

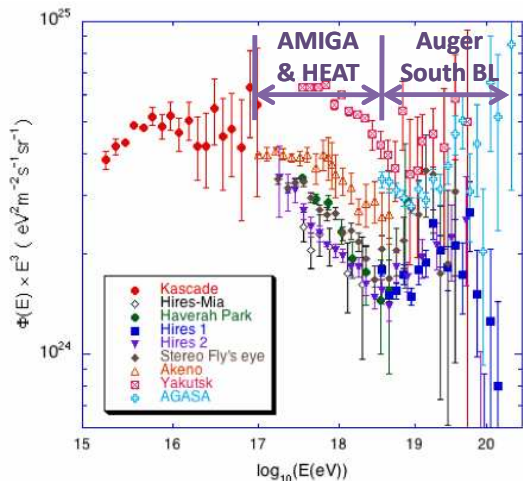


Figure 1: Cosmic ray energy spectrum and its main features: knee (few PeV), second knee (0.5 EeV) and ankle (EeV to few tens of EeV). The energy regions covered by Auger baseline (BL) design and that added by the enhancements AMIGA and HEAT are shown. Adapted from ref. [3].

## Astrophysical characterization of the second knee and ankle

### Observed composition

Certainly, the most relevant scientific result in the energy interval previously defined will be the precise determination of the chemical composition of the primary cosmic ray flux as a function of energy. Several techniques have been used to determine the composition of cosmic rays in the energy region of the enhancements: depth of maximum of the longitudinal distribution,  $X_{max}$ , fluctuations of  $X_{max}$ , muon density, steepness of the lateral distribution function, time profile of the signal and, in particular, rise time of the signal, curvature radius of the shower front, multi-parametric analysis, such as principal component analysis and neural networks, etc.. Unfortunately, the different techniques give conflicting results. The understanding of this inconsistencies is critical to the understanding of the astrophysics of ultra high energy cosmic rays.

At energies above few times  $10^{16}$  eV, the flux is dominated by heavy nuclei. These particles are of Galactic origin. What is being detected is, very

likely, the end of the efficiency of supernova remnant shock waves as accelerators, since the Larmor radii or characteristic diffusion scale lengths of the nuclei become comparable to the radius of the remnants. If there are not more powerful accelerators in the Galaxy [12], the Galactic cosmic ray flux should continue to be dominated by iron above  $10^{17}$  eV and up to the highest energies produced inside the Milky Way. At higher energies, the composition has been measured by several experiments in the past, e.g., Haverah Park, Yakutsk, Fly's Eye, HiRes-MIA prototype and HiRes in stereo mode and, more recently, by Auger [13].

The  $X_{max}$  data suggest that, above  $10^{16.6}$  eV, the composition changes progressively from heavy to light. At the lower limit of the target energy interval, the composition is heavy, possibly iron dominated, in accordance to KASCADE results. Nevertheless, at energies of  $10^{19}$  eV, it is more consistent with a flux dominated by lighter elements.

Despite the fact that there is a consensus among most of the experiments about the reality of this smooth transition, there is no consensus about the rate and extent to which the transition occurs. In fact, the combined data from the HiRes-MIA prototype and HiRes in stereo mode, point to a rapid transition from heavy to light composition between  $10^{17}$  and  $10^{18}$  eV [14]. Beyond that point, the composition would remain light and constant.

The later scenario, however, is not supported by the data of other experiments. Haverah Park, for example, shows a predominantly heavy composition up to  $10^{18}$  eV, followed by an abrupt transition to lighter values compatible with HiRes stereo at around  $10^{18}$  eV. Volcano Ranch, even though there is a single experimental point, is compatible with a heavy composition still at  $10^{18}$  eV, somewhat in accordance to Haverah Park data. Akeno (A1), on the other hand, is consistent with a continuation of the gradual transition from the second knee all across the ankle up to at least  $10^{19}$  eV. The emerging picture is one of great uncertainty, which has deep practical implications and imposes severe limitations on theoretical efforts.

### Cosmic ray propagation

At the energies of the enhancements,  $10^{17} - 10^{19}$  eV, there is a change in the origin, acceleration

and propagation regime of primary cosmic rays. At lower energies, the Galaxy is undoubtedly the source of cosmic rays. Several acceleration mechanisms are certainly at play but it is widely expected that the dominant one is first order Fermi acceleration at the vicinity of supernova remnant shock waves. Nevertheless, theoretically, these Galactic accelerators should become inefficient between  $\sim 10^{17}$  and  $\sim 10^{18}$  eV. This upper limit could be extended to  $\sim 10^{19}$  eV if additional mechanisms were operating in the Galaxy, e.g., compact supernova remnants, spinning inductors associated with compact objects, etc..

At these energies, particles also start to be able to travel from the nearest extragalactic sources in less than a Hubble time. Consequently, at some point above  $10^{17.5}$  eV a sizable cosmic ray extragalactic component should be detectable, probably becoming dominant above  $10^{19}$  eV. Therefore, it is expected that the cosmic ray flux detected between the second knee and the ankle of the spectrum is a mixture of the Galactic and extragalactic components, highlighting the astrophysical richness and complexity of the region.

The Galaxy is a magnetized medium, with a field structured on scales of kpc and typical intensities of the order of some few micro Gauss. This transforms the Galaxy in an efficient confinement region for low energy charged particles. The confinement region is a flattened disk of approximately 20 kpc of radius and thickness of the order of a few kpc. The Larmor radius of a nucleus of charge  $Ze$  can be conveniently parameterized as  $r_{L,kpc} \approx \frac{1}{Z} \times (E_{EeV} / B_{\mu G})$  where  $E_{EeV}$  is the energy of the particle in units of  $10^{18}$  eV and  $r_{L,kpc}$  is expressed in kpc. Protons with energies  $\gtrsim 10^{17}$  eV have gyroradii comparable or larger than the transverse dimensions of the effective confinement region and, therefore, can easily escape from the Galaxy. On the other end of the mass spectrum, just the opposite occurs for iron nuclei that, even at energies of the order of  $10^{19}$  eV, have gyroradii  $< 10^2$  pc and must be effectively confined inside the magnetized interstellar medium.

Therefore, along the energy region targeted by the enhancements, extending from the second knee up to almost the end of the ankle, all nuclei from p to Fe, i.e.  $1 < Z < 26$ , experience a transition in their propagation regime inside the interstellar

medium changing gradually from diffusive to ballistic as the energy increases.

Large statistics and a thorough knowledge of the acceptance across the ankle and second knee, should make possible to measure large scale anisotropies potentially associated with the galactic/extragalactic transition.

Furthermore, extragalactic cosmic rays start to penetrate inside the Galactic confinement region. However, extragalactic particles must first be able to reach us from the nearest Galaxies in less than a Hubble time.

A crude approximation to these effect can be made by assuming a Bohm diffusion coefficient, which implies a travel time for extragalactic cosmic rays  $\tau_{Myr} \approx 10 \times D_{Mpc}^2 \times Z \times \left( \frac{B_{\mu G}}{E_{EeV}} \right)$ . This shows that there is a rather restrictive magnetic horizon. Basically, no nucleus with energy smaller than  $10^{17}$  eV is able to arrive from regions external to the local group ( $D \sim 3$  Mpc) if indeed the intergalactic fields have  $nG$  strengths. Taking as a minimum characteristic distance  $D = 10$  Mpc, only protons with  $E > 2 \times 10^{17}$  eV, or Fe nuclei with  $E > 5 \times 10^{18}$  eV are able to reach the Galaxy in less than a Hubble time.

Therefore, it is at the energies of the second knee and the ankle that different nuclei start to arrive from the local universe. Concomitantly, at these same energies, the magnetic shielding of the Galaxy becomes permeable to these nuclei, allowing them to get into the interstellar medium and, eventually, to reach the solar system. Effectively, the energy interval from  $\sim 2 \times 10^{17}$  to  $10^{19}$  eV is the region of mixing between the Galactic and extragalactic components of cosmic rays.

At energies smaller than  $\sim 10^{19.2}$  eV the dominant process is the photo-production of electron-positron pairs in interactions with the CMBR. In fact, the structure of the ankle can be explained exclusively as a result of pair photo-production by nucleons travelling cosmological distances between the source and the observer [15].

The enhancements are designed to operate in the energy region where the superposition of the Galactic and extragalactic spectra takes place. This is a theoretically challenging region where the smooth matching of the two rapidly varying spectra has yet to be explained. It must be noted that,

even if the shape of the spectrum is important, it is by far insufficient to decipher the underlying astrophysical model. The variation of the composition as a function of energy turns then into the key to discriminate both fluxes and to select among a variety of theoretical options.

There is an additional problem at very high energies above the threshold for pion photo-production. When the statistics are low, different astrophysical scenarios can produce energy spectra experimentally indistinguishable at very high energy [16]. This degeneracy, beyond few times  $10^{19}$  eV, can only be broken with supplementary information coming either from higher energy neutrinos or from composition measurements at lower energies, in the region of the second knee and ankle.

### Composition at injection and the ankle

Power law spectra injected at cosmological sources with different compositions can produce experimentally very similar spectra at the highest energies. Nevertheless, they can be distinguished at smaller energies in the ankle region.

In particular, a purely protonic flux can reproduce the ankle feature solely as an effect of photo production of electron-positron pairs in interactions with the CMBR. In this case, the transition between the Galactic and extragalactic fluxes must be located at the second knee or very near to it.

In the case of a heavier mixed composition injected at the sources, the ankle must be the result of the competition between the Galactic and extragalactic spectra. Moreover, the composition will be a strong function of energy inside this interval, giving an additional tool to assess details of the astrophysical model.

### Conclusions

Auger, in its baseline design, is an excellent instrument for the determination of cosmic ray observables at the highest energies, with particular emphasis in the resolution of the GZK controversy, the search for extragalactic point sources, and the discrimination between bottom-up and top-down production models. However, it has become

increasingly clear that further discrimination between astrophysical models requires the knowledge of the evolution of the cosmic ray composition along the transition region starting at the second knee and encompassing the ankle, i.e. from few times  $10^{17}$  eV to  $\gtrsim 10^{19}$  eV. This energy range is not thoroughly covered by the present configuration of the Auger Observatory, which is fully efficient only above  $3 \times 10^{18}$  eV.

The determination of the composition and its energy dependence inside the transition region is a primordial objective of the enhancements. Working in conjunction with the baseline Auger SD and FD detectors, the enhancements will aid in a fundamental way to our understanding of ultra-high energy cosmic rays in its astrophysical context.

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