The energy spectrum of ultra-high energy cosmic rays measured at the Pierre Auger Observatory and at the Telescope Array

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The energy spectrum of Ultra High Energy Cosmic Rays (UHECRs) provides essential information on the most energetic phenomena in the Universe. Beyond EeV energies, the Telescope Array and Pierre Auger Observatory have the largest exposures to UHECRs ever accumulated in the Northern and Southern hemisphere respectively. The results show independently a steepening of the energy spectrum above a few tens of EeV. However, the comparison of the spectra shows differences that are not explicable in terms of an overall uncertainty on the energy scale used to reconstruct the extensive air showers. The differences are also observed in the region of the sky covered by both instruments, where the spectra should be in agreement within uncertainties when directional-exposure effects are accounted for. For this contribution, a working group from both Collaborations examined these differences considering the energy-dependent systematic uncertainties. A special focus is given to the characterization of the spectral features, which provide an accurate tool to enhance our understanding of the comparisons.

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1. Introduction

Cosmic rays compose less than one particle out of ten million in the interstellar gas. Still, their average energy density is similar to the one of the gas. A small proportion of particles has therefore appropriated a substantial part of the available energy. The study of the energy spectrum of cosmic rays, providing the differential intensity (flux per steradian) of cosmic protons and nuclei as a function of energy, is thus one of the cornerstones of astroparticle physics.

Because of the very small value of the cosmic-ray intensity at high energies – less than one particle per km$^2$ yr sr above 10 EeV –, the construction of giant observatories has been necessary to collect an increased influx of events. The Pierre Auger Observatory, located in the province of Mendoza (Argentina) and covering 3000 km$^2$, has been allowing since 2004 a scrutiny of the UHECR intensity – except in the northernmost quarter. Another scrutiny, mainly of the Northern sky, has been provided by the Telescope Array (TA), located in Utah (USA) and covering 700 km$^2$, operating since 2008. These latest-generation experiments have allowed an unprecedented sensitivity in measuring the UHECR energy spectrum.

The object of this joint contribution is to review the different energy spectrum measurements made at these observatories in the last decade in the quest to decipher the UHECR origin. Both observatories are hybrid cosmic-ray detectors that consist of fluorescence telescopes overviewing an array of surface detectors (SD). The fluorescence detectors (FD) provide an accurate determination of the cosmic-ray energies by measuring the longitudinal developments of the extensive air showers in a nearly calorimetric manner. Their duty cycle is however limited to about 15%. It is thus advantageous for both Auger and TA to use their SD arrays to measure the energy spectrum at the highest energies, by propagating the FD energy scale to the SD thanks to a subset of events simultaneously detected by the FD and SD.

Although the techniques for assigning energies to events are nearly the same, there are differences as to how the primary energies are derived at both observatories, and differences in the energy spectrum estimates. Currently, systematic uncertainties in the energy scale of both experiments amount to about 14% (Auger) and 21% (TA). This encompasses the adopted fluorescence yield, the uncertainties in the absolute calibration of the FD, the influence of the atmosphere transmission used in the reconstruction, the uncertainties in the shower reconstruction, and the uncertainties in the correction factor for the missing energy. Uncovering the sources of systematic uncertainties in the relative energy scale is ultimately motivated to understand the differences in the energy spectra, in particular at the highest energies. To this aim, a joint working group has been formed between both Collaborations at the first UHECR conference, held in 2010 in Nagoya (Japan). Notable results of this joint effort are $i$) the successful demonstration that the Auger-TA energy scale difference can be explained by the different fluorescence yield and invisible energy models used in the respective analyses, $ii$) the persistent energy-dependent differences between the spectra above $\sim 10$ EeV after a global rescaling of the respective energy scales by $+5.2\%$ for Auger and $-5.2\%$ for TA that allows for getting consistent spectra in the ankle-energy region, and $iii$) the critical scrutiny of energy-dependent systematic uncertainties leading to possible non-linearities in the $[10-100]$ EeV decade of $\pm 3\%$ for Auger and $(-0.3 \pm 9)\%$ for TA, which are below the required $+10\%$ per decade (Auger) and $-10\%$ per decade (TA).

On top of a global consistency modulo a global energy scale factor, there is thus a remaining
source of discrepancy above $\simeq 10$ EeV not yet identified. In this contribution, we update the comparisons carried out in the previous studies. At the time of writing (July 2019), the contents of this article are based on previously published analyses [1, 2]. They will be updated in the final proceedings.

2. Energy spectra

The left panel of Figure 1 shows the TA [1] and Auger [3] energy spectra calculated over their entire fields of view. After adjusting the energy scales of the two experiments, Auger and TA spectra are in good agreement around the ankle region but a large discrepancy above $\simeq 20$ EeV remains.

![Figure 1](image_url)

**Figure 1:** Energy spectra over the entire fields of view for TA [1] and Auger [3]: (left) calculated using the nominal energy scales of TA and Auger, (right) calculated after applying the overall $+5.2\%$ (Auger) and $-5.2\%$ (TA) energy scale corrections. Significant difference between the Auger and TA energy spectra remains after rescaling the TA and Auger energies by constant (energy-independent) factors.

As pointed out in Section 1, although the TA and Auger techniques of reconstructing SD event energies are very similar, there do exist differences in their respective instruments and the methods of how the final primary energies are assigned. The systematic uncertainty in the overall energy scale is $14\%$ for Auger and $21\%$ for TA, while the uncertainties due to the exposure and the unfolding of the effects of the resolution are subdominant. As the right panel of Figure 1 shows, the Auger and TA spectra are in a good agreement in the ankle region (from $10^{18.4}$ eV to $\simeq 10^{19.4}$ eV), when the Auger energies are increased by $5.2\%$ and the TA energies are reduced by $5.2\%$. Such shifts are well within the stated uncertainties in the energy scales of both experiments. A large difference remains above $\simeq 10^{19.5}$ eV, in the region of the suppression.

To determine whether the remaining differences in the region of the high energy suppression are an instrumental or an astrophysical effect, we have performed a comparison of Auger and TA spectra in the common declination band, a range of declination values that is in the field of view of both experiments: $-15.7^\circ < \delta < 24.8^\circ$. In this work, we use the Auger and TA analyses with upper limits on the event zenith angles of $60^\circ$ and $55^\circ$, respectively. Moreover, for the purposes of this comparison, we use a spectrum calculation technique that takes into account the details of the Auger and TA exposure dependence on the declination [2].
3. Comparison of the TA and Auger spectra in the common declination band

Figure 2 shows the directional exposures of the two experiments. For the Auger vertical analysis that covers declinations from −90° to 24.8°, the total exposure is 51,588 km² sr yr. For the TA analysis with event zenith angles extending to 55°, the total exposure is 8,300 km² sr yr. TA is sensitive in the declination range from −16° to 90°.

To calculate and compare the Auger and TA spectra in the common declination band (shaded area in Figure 2), we use the following method:

\[
J_{1/\omega}(E) = \frac{1}{\Delta\Omega \Delta E} \sum_{i=1}^{N} \frac{1}{\omega(\delta_i)}
\]

where \(J_{1/\omega}(E)\) is the differential flux \(J\) as a function of energy \(E\), calculated by this "1/\omega - method". \(\Delta\Omega = 2 \pi \int_{\delta_{\text{min}}}^{\delta_{\text{max}}} d\delta \cos(\delta)\) is the solid angle covered by the common declination band (\(\delta_{\text{min}} = -15.7°\), \(\delta_{\text{max}} = 24.8°\)), \(\omega\) is the directional exposure shown in Figure 2, and \(\delta_i\) is the declination of the \(i^{th}\) event. The sum is over \(N\) events in the energy interval \(\Delta E\). The statistical uncertainty of \(J_{1/\omega}(E)\), if one were to ignore any anisotropies, is given by (to first order):

\[
\Delta J_{1/\omega}(E) = \frac{1}{\Delta\Omega \Delta E} \left\{ \int_{\delta_{\text{min}}}^{\delta_{\text{max}}} d\delta \omega(\delta) \cos(\delta) \right\}^{1/2} \sqrt{N}.
\]

For the formal derivation of this method, as well as the cross-checks with the standard TA and Auger spectrum calculation techniques, see [2]. The Left panel of Figure 3 shows the results with Auger and TA energies scaled by ±5.2% (as in the right panel of Figure 1). When we fit the two results, \(J_{1/\omega}^{\text{Auger}}\) and \(J_{1/\omega}^{\text{TA}}\), to broken power law functions, the high energy cutoff points become only 0.6σ different: \(\log_{10}(E/\text{eV}) = 19.59 \pm 0.04\) for TA, and \(\log_{10}(E/\text{eV}) = 19.56 \pm 0.03\) for Auger. This agreement is an important step towards comparing the results of the two experiments.
Auger and TA UHECR energy spectrum

Olivier Deligny

Figure 3: Left: Auger SD (red squares) and the TA SD (black circles) spectra in the common declination band, calculated using the $1/\omega$ method. The Auger energy scale has been increased by 5.2% while the TA energies have been decreased by 5.2%, as it was done in the right panel of Figure 1. Right: Ratio of the Auger ($J_{\text{Auger}}$) and TA ($J_{\text{TA}}$) fluxes that have been calculated using the $1/\omega$ method.

However, differences still remain, as it can be seen in the right panel of the Figure 3: the ratio of fluxes $J_{\text{Auger}}/J_{\text{TA}}$ in the common declination band, depends on energy in a significant way.

Figure 4: Left: Auger spectra covering the sky to the South of the common declination band (shown in blue), common declination band (shown in red), and the combination of the two (shown in black). Right: TA spectra for two declination bands: common declination band (in red) and over the rest of the northern hemisphere (in black).

$-15.7^\circ < \delta < 25.0^\circ$, and $-90.0^\circ < \delta < 25.0^\circ$, are in good agreement among each other. In the case of TA, on the other hand, the situation is different: as Figure 4-right shows, the break point (using the broken power law fit) in the spectrum for lower declinations $-16^\circ < \delta < 24.8^\circ$ occurs at $\log_{10}(E/\text{eV}) = 19.59 \pm 0.06$, while for $24.8^\circ < \delta < 90^\circ$, the second break point occurs at $\log_{10}(E/\text{eV}) = 19.85 \pm 0.03$. Note that the cutoff energy in the common declination band is in good agreement with that of Auger, but is different from the TA Northern sky with the post-trial
significance of 4.3 $\sigma$.

It should be noted that although the spectrum calculations in Figures 4 left and right used traditional Auger and TA methods, cross-checks have been made [3, 1], and it was shown that the $1/\omega$ method produced similar results [2].

4. Systematic uncertainties of the TA and Auger energy spectra

We consider here the energy-dependent systematic uncertainties in the analyses of the two experiments. Since the detector types, reconstruction and analysis methods are different for TA and Auger, the approaches for quoting the energy-dependent uncertainties for the two experiments will be somewhat different too. Below, we consider the important categories of the energy-dependent sources of the systematic uncertainties and summarize the results for each experiment.

4.1 Aerosols

Since higher-energy showers are brighter, the distances from which the fluorescence detectors can see them increase with energy. Because the effects of the atmospheric light attenuation must be taken into account in determining the energy of the shower, an uncertainty in the atmospheric attenuation parameters can lead to an energy-dependent reconstruction bias for the fluorescence detector that can propagate to the calibration of the surface detector energy scale by the fluorescence detector.

Figure 5-left shows the systematic check for TA. We generate a Monte Carlo sample of TA hybrid events [4] using the mean vertical aerosol optical depth (VAOD) of 0.04 and then reconstruct this simulated showers using the VAOD values of 0.04 and 0.034, which would be an extreme case scenario for TA. We then plot the natural logarithm of the ratio of the reconstructed and generated energy versus the logarithm of the generated Monte Carlo energy for the values of the VAOD of 0.04 and 0.034. We find that in the extreme case scenario, the energy-dependent reconstruction bias is only 1.7% per energy decade for TA.

Figure 5-right shows the study of the energy-dependent biases due to the aerosols done at the Auger Observatory. As can be seen from Figure 5-right, the energy-dependent bias obtained changing the VAOD by its uncertainty is expected to be of the order of 1% per decade of energy for Auger. In addition, the ratio of the surface detector and the fluorescence detector energies was examined versus the aerosol transmission to the shower maximum. No apparent energy reconstruction bias was found with respect to the aerosol transmission [5].

4.2 SD and FD energy comparison

Since the Auger and TA FD provide a reliable calorimetric reconstruction of the UHECR energy, one can assess the nonlinearities of the Auger and TA SD energies by comparing the SD and FD energy reconstructions of the same cosmic-ray events.

The ratio of the TA SD energy to the TA FD energy scrutinized versus the energy for the events that have been simultaneously seen by the TA FD and the TA SD shows that the size of a possible nonlinearity of the TA energy is constrained to $-2\%\pm9\%$. The comparison has been done for two methods of reconstruction of the TA SD energy: using the attenuation correction derived from proton Monte Carlo showers simulated with QGSJET-II.3 and using the model-independent,
constant intensity cut, attenuation correction. In addition, it is worth noting that the TA SD constant intensity cut method and the shower attenuation correction derived from the TA SD Monte Carlo yield energies that agree at a ~ 3% level with no net bias.

The Pierre Auger Collaboration has conducted this study, also. With the large exposure of the Auger Observatory, the calibration parameters used to convert the shower size at ground level into energy are determined with a statistical uncertainty at the 1% level and it is also possible to study the linearity of the energy in different declination bands. The ratio of the Auger SD to FD energy shows deviations from unity less than 2% per decade of energy. In addition, such nonlinearities are less than 1% when the Auger SD to FD ratio above $10^{19}$ eV is scrutinized versus declination.

5. Summary

We have reviewed and compared the results of the UHECR spectra measured by the Pierre Auger and Telescope Array experiments. It was established that scaling the energies of Auger and TA by +5.2% and -5.2%, respectively, brings the two measurements into a good agreement around the ankle region from $10^{18.4}$ eV to $\approx 10^{19.4}$ eV. Energy scaling of 5.2% is well within the systematic uncertainties stated by the experiments. At the energies around the suppression region, on the other hand, we have found that even after restricting the comparison to the region of the sky that is observed by both experiments, there is agreement in the position of the cutoff energies.
Statistically significant differences remain, however: a relative nonlinearity between the TA and Auger energies of the order of 20% per decade of energy exists above 10 EeV. We have investigated the systematic uncertainties of TA and Auger that would produce the energy-dependent biases in their energy spectra, and we have found that such biases are constrained to $-0.3 \pm 9\%$ for TA and $\pm 3\%$ for Auger. We have not identified the sources of the remaining discrepancies at this time.

We have also reviewed the energy spectra in the declination bands to which only one of the two observatory has access to. All three Auger spectra, for declinations $-90^\circ < \delta < -15.7^\circ$, $-15.7^\circ < \delta < 25.0^\circ$, and $-90.0^\circ < \delta < 25.0^\circ$, are in a good agreement among each other. In the case of TA, on the other hand, the situation is different: the break point (using the broken power law fit) in the spectrum for lower declinations $-16^\circ < \delta < 24.8^\circ$ occurs at $\log_{10}(E/eV) = 19.59 \pm 0.06$, while for $24.8^\circ < \delta < 90^\circ$, the second break point occurs at $\log_{10}(E/eV) = 19.85 \pm 0.03$. Note that the cutoff energy in the common declination band is in good agreement with that of Auger, but is different from the TA Northern sky with the post-trial significance of 4.3 $\sigma$.

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