Evidence for Declination Dependence of the Ultrahigh Energy Cosmic Ray Spectrum in the Northern Hemisphere

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ABSTRACT

Telescope Array (TA) is the largest experiment in the Northern Hemisphere studying ultrahigh energy cosmic rays. TA measurements of the cosmic ray spectrum using the surface detector have the best statistical power in the experiment, and observe the ankle of the spectrum and the high energy cutoff. When the data are divided into two declination bands, above and below 24.8 degrees, the cutoff appears at $10^{19.64\pm0.04}$ $(10^{19.84\pm0.02})$ eV in the lower (higher) band, an energy difference of 58%. The global significance of the difference is 4.3 standard deviations. The lack of an instrumental cause of this difference implies it is astrophysical in nature.

Keywords: cosmic ray spectrum, declination dependence, telescope array surface detector

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1. INTRODUCTION

The Telescope Array experiment, described previously by Abu-Zayyad et al. (2013a, 2012a,b), has the aim of studying ultrahigh energy cosmic rays. TA measurements have been made of the spectrum (Abu-Zayyad et al. 2013b) and composition (Abbasi et al. 2018) of cosmic rays. Searches for anisotropy (Abbasi et al. 2014) and other results (Abbasi et al. 2019) have also been published. In this paper we report on a study of the energy of the high energy cutoff seen in different parts of the sky.

The spectrum may cut off at high energies, $E_c > 5 \times 10^{19} \text{ eV}$, as the result of pion photoproduction in proton interactions with photons of the cosmic microwave background (CMB) radiation, (Greisen 1966; Zatsepin & Kuzmin 1966), of photodissociation of cosmic ray nuclei, or simply at the maximal energy to which astrophysical sources can accelerate cosmic rays.

Because of a less powerful energy loss mechanism, $e^+e^-$ pair production in the interactions of proton with the CMB, the energy of the cutoff could also vary according to the distance to the closest sources strong enough to produce particles at the highest energies. The first observation of the cutoff, at the energy predicted in Berezinsky & Grigor’eva (1988), was made in the Northern Hemisphere sky by the High Resolution Fly’s Eye (HiRes) experiment, (Abbasi et al. 2008). Two subsequent measurements were made by the Pierre Auger Observatory (Auger) (Abraham et al. 2010) (at a lower energy than that predicted by (Berezinsky & Grigor’eva 1988), and in the Southern Hemisphere) and by TA (Abu-Zayyad et al. 2013b) (at the same energy as HiRes, and also in the Northern Hemisphere).

This study followed originally from a working group (Verzi et al. 2017) formed from members of the TA and Auger collaborations to consider differences in the two experiments’ spectrum measurements. Auger has a surface detector (SD) of about 1600 Cherenkov tanks located on the Pampa Amarilla in Argentina. Part of the spectral difference seems to come from an energy scale difference between the two experiments, but even if a correction is made for this, the cutoff appears at different energies in the two experiments’ results. Figure 1a shows the two spectra after making the correction for energy scale difference. To isolate effects that could produce the difference in cutoff energy, the working group then studied the spectra measured in the declination band common to both experiments. This band stretches from $-15$ degrees of declination (the lowest observable by TA) to 24.8 degrees (the highest observable by Auger). Figure 1b shows the two spectra in the common declination band, again after correction for energy scale difference. The two measurements of the energy of the cutoff are consistent in the common declination band. These surprising results indicate that the spectrum in the Northern Hemisphere varies with declination.

In Section 2 we describe the surface detector of TA. In Section 3 we examine further the TA and Auger spectra in the common declination band. In Section 4 we present the results of the study. In Section 5 we describe a search for an instrumental cause of the cutoff energy difference. And in Section 6 we present a summary.

2. THE SURFACE DETECTOR OF THE TELESCOPE ARRAY

Each of the 507 detectors of the SD consists of two scintillation counters, each of 3 m² area, viewed independently by photomultiplier tubes. Scintillation light is collected and brought to the phototubes by wavelength-shifting fibers embedded in grooves on the scintillator. Each channel undergoes a flash analog-to-digital (FADC) conversion every 20 ns, and the result is saved for several seconds. A radio system connects each counter with one of three radio control towers...
spaced around the array, each controlling about 1/3 of the array. Once per second the tower polls each counter in its area to read out the times that the counter has recorded a signal of strength 3 times what a minimum ionizing particle (MIP) would provide (Abu-Zayyad et al. 2013a). If three adjacent counters report signals within 8 µs of each other the array is triggered. Then the radio tower commands each counter that has a signal of strength 1/3 MIP or more to provide its FADC traces. These are written into the data event record. The radio towers communicate with each other when triggered counters are near the area boundaries to collect all possible detector signals.

Every 10 minutes each detector is commanded to upload a variety of information about its performance. In 10-minute periods each scintillation counter accumulates a histogram of pulse heights for single muon events by triggering on coincidences between the two counters. This histogram forms the basis for calibrating the counter signals in MIP units. The peak height and RMS value are used in the data analysis and Monte Carlo simulation.

The data analysis starts with identifying clusters of counters struck by the particles in a cosmic ray air shower. The times when counters are struck are used in reconstructing the arrival direction of the cosmic ray. The signal size and times are used to calculate the center of the shower, and counters’ pulse heights and distances from the center are used to calculate $S_{800}$, the signal at a distance of 800 m from the shower center, by interpolation. To reconstruct the energy of the cosmic ray primary particle, the $S_{800}$ value and zenith angle are compared to Monte Carlo simulations of the SD (Abu-Zayyad et al. 2013b). Figure 2a shows the relation between $S_{800}$ and zenith angle for Monte Carlo events of various energies. As a check on this method of energy reconstruction we also use the constant-intensity-cut (CIC) reconstruction method (Hersil et al. 1961). Figure 2b shows a scatter plot of the two energy values for each event: CIC based vs Monte Carlo based. The agreement between the two methods is excellent. In both cases the SD energy was compared with the energy of the TA fluorescence detector (FD) for events where a good reconstruction is possible.
by both detectors. Since the FD energy determination is calorimetric this gives us a robust energy reconstruction for SD events. The TA SD is approximately 100% efficient for cosmic rays energies above about $10^{18.9}$ eV.

Figure 2. TA SD event energies were reconstructed using an energy estimation table (Ivanov et al. 2016) derived from the Monte Carlo, shown in (a), and using the Constant Intensity Cut method (Hersil et al. 1961). The scatter plot in (b) shows the comparison between the two different reconstruction methods applied to the TA SD data. The standard deviation of the logarithmic difference of the energies reconstructed by the two methods was $\sim 3\%$.

3. THE TA AND AUGER SPECTRA IN THE COMMON DECLINATION BAND

In Figure 1b we saw that the cutoff energies of the TA and Auger spectra are consistent in the common declination band. The two spectra are not identical, however, and in this section we examine the origin of the remaining difference.

In order to characterize the difference between the Auger and TA spectra in the common declination band, we performed a simultaneous fit to the two spectra. This fit assumes there are three power law sections separated by two break points (we include the recently seen shoulder at $10^{19.2}$ eV (Aab et al. 2020a) in our fits). The result is shown in Figure 3. It has a chi-squared of 38.5 for 25 degrees of freedom. Because the Auger spectrum is based on about six times the number of events as TA, the fit follows the Auger spectrum more closely than that of TA. Above an energy of $10^{19.5}$ eV the TA data points can be seen to be about 15% higher than those of Auger.

To understand how often such a difference could arise randomly, we constructed a model of the TA and Auger spectrum measurements. It included the spectrum as found in the simultaneous fit from the previous paragraph, the energy resolution, the correction for bin migration, the anisotropy dipole seen by the Auger collaboration, and the excess of events called the hotspot seen by the TA collaboration. We note that the TA spectrum in the common declination band has highest statistical power at the northern end of the band where the hotspot enters, while the Auger spectrum is
weighted at the southern end away from the hotspot. We threw the model with the observed number of TA and Auger events 100,000 times and found that \( \sim 10\% \) of the time there was a divergence between the two spectra of similar size or larger as that of the data. We conclude that the observed difference between the TA and Auger spectra in the common declination band may be due to a statistical fluctuation.

One could imagine an energy dependent change in the energy resolution producing a resolution function with a longer tail than Auger’s above \( 10^{19.4} \) eV. However, a straightforward application of such a hypothesis to the data with \( \delta > 24.8^\circ \) would lead to a contradiction, since that spectrum has a steeper fall off than the \( \delta < 24.8^\circ \) data. The remaining possibility that the resolution function has both an energy and a declination dependence (via the zenith angle) is ruled out in Section 5.

4. RESULTS: THE CUTOFF ENERGY VARIES WITH DECLINATION

Figure 4b shows the spectra of ultrahigh energy cosmic rays measured with the SD of the Telescope Array above and below 24.8 degrees in declination. Data collected during the first 7 years of TA operation are included in this figure, corresponding to the time the TA collaboration first noted this effect (Ivanov et al. 2017). In the figure a broken power law fit was performed to the data to quantify the energy of the cutoff. The characteristics shown in Figure 4a are (1) the cutoff energy in the lower declination band, shown in red, agrees within 1/2 standard deviation with the Auger result; (2) the cutoff energy in the higher declination band is higher than that seen by TA in the whole sky; and (3) the data in both declination bands are well fitted by a broken power law model.

We calculate the significance of the difference in cutoff energies first by using the fit values of the cutoff energies and uncertainties (Ivanov et al. 2017) and get a significance of 3.9 standard
deviations. This is called the “local significance.” To determine the probability that this difference could arise by chance, a Monte Carlo calculation was carried out. In this calculation trials with the same number of events as the data were generated, with the events placed randomly according to the TA aperture, and with energies chosen according to the whole-sky spectrum of TA. The spectrum was then calculated for the two regions of declination, and trials were counted in which the three characteristics of the spectra listed in the previous paragraph were true and the cutoff energy was different in the two regions as much as or more than the data. The result is called the global significance and is 3.5 standard deviations (Ivanov et al. 2019a).

Figure 4c shows the spectra in the two declination intervals for years 8–11 of TA operation. Here we see that the effect persists. Figure 4a shows the spectra for the whole 11 years of TA data (Ivanov et al. 2019b). The local significance is 4.7 standard deviations, and the global significance is 4.3 standard deviations. In 11 years of TA SD data, there are 10 365 events above $10^{18.8}$ eV, and the analysis details are described in Ivanov et al. (2019b).

5. SEARCH FOR AN INSTRUMENTAL CAUSE OF THE EFFECT
In the previous section we saw that there is strong evidence that the spectrum of ultrahigh energy cosmic rays, measured by the TA surface detector, varies with declination. The question now arises, is this an instrumental effect arising from some feature of the TA SD analysis or is the effect astrophysical in origin.

We have searched for an instrumental cause in many ways such as a possible nonlinearity in FD event reconstruction or a nonlinearity in FD/SD energy comparison and found no evidence for these effects (AbuZayyad et al. 2019).

A stringent test of a north-south spectrum difference is to search for an east-west spectrum difference. The grid of the TA SD layout lies along north-south and east-west axes, so an instrumental effect would appear in the east-west direction also. In particular, an acceptance effect, which could be a function of zenith angle, or a nonlinearity in energy assignment would also appear in an east-west direction. Figure 5a shows a plot of zenith angle vs. azimuthal angle with the left u-shaped curve indicating the locus of points whose declination is 24.8 degrees. Events inside and above the curve are below 24.8 degrees. A simple translation of the formula for this curve allows us to look at a similar difference in an east-west direction, as also shown in the figure. The test consists of measuring the spectrum using events above and, independently, below the curve on the right in Figure 5a. An instrumental effect would make the spectra different. If the spectra are the same, it would strongly support an astrophysical origin of the north-south difference in cutoff energies, as the whole sky rotates through the east and west regions. Figure 5b shows the test result. The two spectra have the same power laws and cutoff energies, and the point-to-point ratio of the spectra is $1.00 \pm 0.02$. This would not be the case if the difference in cutoff energies above and below a declination of 24.8 degrees were due to acceptance or energy scale. We conclude that this is strong support for the interpretation that the spectrum of ultrahigh energy cosmic rays is different in lower and higher declination bands due to an astrophysical effect.
Figure 5. (a) Angles $\theta$ and $\phi$ represent the zenith and azimuthal angles of the event arrival direction in the local horizontal coordinates of the TA SD. A contour of constant declination $\delta(\theta, \phi) = 24.8^\circ$ is represented by the solid curve, while the dotted curve shows the corresponding contour of the constant modified declination, $\tilde{\delta}(\theta, \phi) = \delta(\theta, \phi - 90^\circ)$. (b) shows the TA SD spectrum measured for $\tilde{\delta} < 24.8^\circ$ and $\tilde{\delta} > 24.8^\circ$. The two spectra agree to within 2%.

6. SUMMARY

The Telescope Array and Pierre Auger collaborations established a working group to study the differences in their measurements of the spectrum of cosmic rays (AbuZayyad et al. 2019). After making an energy scale adjustment of about 10% to bring the ankle region of the two spectra into alignment, there remains a difference in the two spectra in the energy of the high-energy cutoff. The working group then examined the two experiments’ spectra in the band of declination covered by both experiments and found that there the cutoff energies agreed. Although not anticipated by the two collaborations, this is not an impossible result since the energy of the cutoff could vary across the sky due to the maximum energy of different sources, or their distances from Earth.

This result prompted the Telescope Array collaboration to measure the spectrum in the northern part of the sky (above the 24.8 degree limit of the common declination band). The cutoff energy was found to be higher in that region. In the 11 years of TA data that have been collected, the global significance of the difference is 4.3 standard deviations.

A comprehensive search for an instrumental effect to explain the difference has failed to find one, and both the TA collaboration and the joint TA-Auger working group studying the spectrum of ultrahigh energy cosmic rays have concluded that the variation of the cutoff energy with declination is an astrophysical effect.

In a recent paper, Aab et al. (2020b), the Auger collaboration reported that the spectrum in the Southern Hemisphere is independent of declination, which they say may indicate that the sources are common across the Southern Hemisphere sky. The present paper reports strong evidence that
the sky in the Northern Hemisphere is different: the spectrum varies with declination. This may be ascribed to sources that have a higher maximum energy or perhaps are closer to the earth.

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