33RD INTERNATIONAL COSMIC RAY CONFERENCE, RIO DE JANEIRO 2013
THE ASTROPARTICLE PHYSICS CONFERENCE

Progress towards understanding the analyses of mass composition made by the Auger and Telescope Array Collaborations

WILLIAM F. HANLON[1] FOR THE TELESCOPE ARRAY[2] AND PIERRE AUGER COLLABORATIONS[3].

[1] *University of Utah, Department of Physics and Astronomy and High Energy Astrophysics Institute, Salt Lake City, UT, USA*
[2] *http://www.telescopearray.org/index.php/research/publications/conference-proceedings*
[3] *Full author list: http://www.auger.org/archive/authors_2013 05.html*

whanlon@cosmic.utah.edu

Abstract: The composition of cosmic rays at the highest energies is one of the most important problems in UHE cosmic ray physics. Recent results using fluorescence and hybrid fluorescence/surface array detectors (HiRes/Telescope Array/Auger) appear to lead to inconsistent conclusions. Comparison is not straightforward because of different acceptance and resolution of the various experiments. Here we take a 4-component mixture of protons, helium, nitrogen, and iron that varies with energy in such a way that it reproduces the Auger $X_{\rm max}$ data (Auger $X_{\rm max}$ data as obtained with hybrid measurements). We use this mix to simulate air showers in the TA aperture. These events are then passed through the TA detector simulation and reconstructed using TA hybrid methods and cuts. In this paper we describe the method and present the results of the simulations. The results show that the $\langle X_{\rm max}\rangle$ for the Auger mix composition would be observed by TA hybrid (after full event reconstruction) with a bias of 5.2 ± 0.4 g/cm^2, and the pure proton coposition will be observe with a bias of 11.5 ± 0.9 g/cm^2. The difference in the expected $\langle X_{\rm max}\rangle$ (reconstructed by TA-hybrid) between the pure proton and the Auger mix compositions is 20 g/cm^2 at 10^{19} eV, and the present study shows that, given the number of events generated, the Telescope Array would be able to distinguish between these two compositions with a confidence level better than 4 sigmas.

Keywords: Telescope Array, Pierre Auger, UHECR, composition, xmax

1 Introduction

One of the most important goals in particle astrophysics is understanding the chemical composition of ultra high energy cosmic rays (UHECRs). Knowledge of the relative proportions of UHECR species arriving at the earth will constrain models of cosmic ray origin and propagation, which are currently controversial (see [2] for example). Measurement of the UHECR composition in a event-by-event basis at the highest energies is difficult (due to the extremely low flux). Therefore the composition must be inferred indirectly by measuring the depth of shower maximum ($X_{\rm max}$) via fluorescence detection.

For a given shower, the depth of shower maximum depends upon the depth of first interaction (X_0), which decreases with $\log(E_0)$, and the depth over which the shower cascade takes to develop until the mean energy per secondary particle falls below the critical energy at which collision losses exceed radiative losses. Though all of the details needed to model ultra high energy air showers are not completely understood (cross sections, multiplicities, etc.), [1] describes a simple branching model of air shower development, introduced by Heitler, which reveals two important characteristics of the air showers: the $\langle X_{\rm max}\rangle$ is proportional $\ln(E_0)$ (where E_0 is the primary particle energy) and the elongation rate is constant for a given primary particle composition. The elongation rate is defined as $d\langle X_{\rm max}\rangle/d\log E$, which is the change of the mean $X_{\rm max}$ per decade of primary particle energy.

The Heitler model can be extended to showers initiated by nuclei of any given atomic number A by invoking the superposition principle. In this case we can treat the shower as A primary showers each with initial energy E_0/A. Showers initiated by heavier nuclei develop faster (i.e., $X_{\rm max}$ will be smaller). The $X_{\rm max}$ shower-to-shower fluctuations are not described by the simplistic superposition model, because it does not take into account effects from nuclear fragmentation, impact parameter fluctuations, etc. However, the $X_{\rm max}$ fluctuations are expected to reduced for larger A due to averaging effects. We therefore expect the width of the distribution of $X_{\rm max}$ to be sensitive to the primary particle as well.

The distribution of $X_{\rm max}$ observed in a given energy bin is dependent upon the statistical fluctuations of shower development (depth of first interaction and cascade development) in the atmosphere as well as upon the resolution of the detector. Using the Heitler model we expect a spectrum composed of light particles (e.g. protons) to have larger mean $X_{\rm max}$ and a distribution width larger than that of a heavier species (e.g. iron). Additionally if the composition is unchanging over different energy ranges the elongation rate will remain constant.

Telescope Array (succeeding the HiRes experiment) with 750 km^2 of collecting area, described in [3] and [4], and the Pierre Auger Observatory with 3000 km^2 of collecting area, described in [5], are the 2 largest cosmic ray observatories. Both deploy large surface arrays to detect charged particles (and protons in the case of Auger) which reach the Earth's surface, as well as multiple fluorescence telescopes placed around the array, to observe UV light caused by the electromagnetic cascade of the air shower. While $X_{\rm max}$ is determined by using the shower profile as observed by the fluorescence detectors, folding in the geometry and timing information of the surface detectors for those showers that trigger them can improve the profile fit and further constrain

X_{max}. In [6], HiRes reported measuring a lighter composition composed primarily of protons above $10^{18.2}$ eV. The Pierre Auger collaboration reported in [7] measurements of the first two moments of the X_{max} distribution, the mean and the RMS, above 10^{18} eV with narrowing X_{max} widths above $3 \times 10^{18.5}$ eV, indicating a composition possibly changing from lighter to heavier species.

At the UHECR 2012 conference in Geneva, Switzerland in March 2012 the Auger and Telescope Array (TA) collaborations formed a Mass Composition Working Group (MCWG) to discuss how the two groups could work together to resolve outstanding differences in the interpretation of conflicting X_{max} data [8]. It was decided that Auger would provide simulated data which resembles the Auger X_{max} distributions. This simulated data would be reconstructed through the TA analysis software to examine the effects of reconstruction of Auger X_{max} input with TA detector effects folded in and then compare those results with observed X_{max} as seen in TA data. In particular, the question of whether TA detector resolution and number of events would prevent TA from seeing a changing composition or a composition that is heavier than protons at the highest energies, could be addressed.

2 Data Analysis

Auger created an *ad hoc* model of UHECR composition by examining their data published in [9], and fitting it with a 4-component mixture. The model is called *ad hoc* because it is not claimed to be a physical model of what the actual cosmic ray beam contains. Using a reasonable choice of 4 input species, proton, helium, nitrogen, and iron the best proportions were found by fitting the expected X_{max} distributions to the Auger X_{max} data distribution. The four species fractions were found for each energy bin. Figure 1 shows the χ^2 fits Auger performed on their X_{max} data using a 4-component model. The 4-component fractions found using that fit was used to generate the Monte Carlo studied in this paper. The left figure compares the fit (red points) to the data (black points) $\langle X_{max} \rangle$ and the right compares the fit and X_{max} widths. There is a ~ 8 g/cm^2 bias between the means from the fit and the data which is caused by low statistics in the tails of the X_{max} distributions. A maximum likelihood fit was later performed reducing the bias in the means and is shown in figure 2. However we used the fractions of the 4-component mixture found from the χ^2 fits in the present analysis.

TA generated a Monte Carlo set of ~ 4 million events using the 4 input species in the same relative proportions as described by the Auger mixture weighted to the HiRes1 and HiRes2 combined mono spectra shown in [10] in 0.1 decadal bins. Events that triggered the surface detector array and at least 1 of the 2 fluorescence detectors ("hybrid" events) were accepted for analysis. A TA surface array trigger consists of 3 SDs counters, above 3 MIP each, within an 8 microsecond window (as described in [3]). A TA FD trigger consists of at least 5 adjoining PMTs above night sky background within a coincidence window of 25.6 microseconds (as described in [11]).

Auger claims to reconstruct shower X_{max} with very little bias due to fiducial volume cuts based on each shower's geometry. We expect then that Auger data should closely resemble the $\langle X_{max} \rangle$ from the input (thrown) Monte Carlo. Figure 3 compares the $\langle X_{max} \rangle$ of the Auger data described in [9] with the thrown $\langle X_{max} \rangle$ of the composition mixture

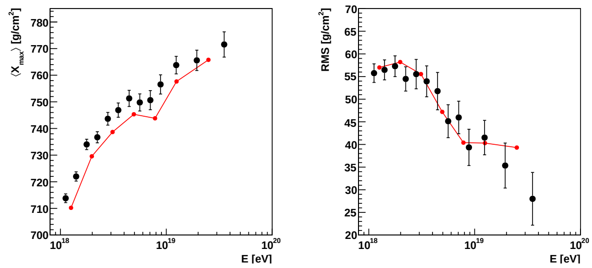

Figure 1: Comparing the Auger values for $\langle X_{max} \rangle$ (left) and RMS(X_{max}) (right) [9] with the ones obtained from the 4-component model studied in this paper (red points). The 4-component model was obtained with a χ^2 fit to the Auger X_{max} distributions. There is 8 g/cm^2 difference between the fit and data in the $\langle X_{max} \rangle$ caused by low statistics in the tails of the X_{max} distributions.

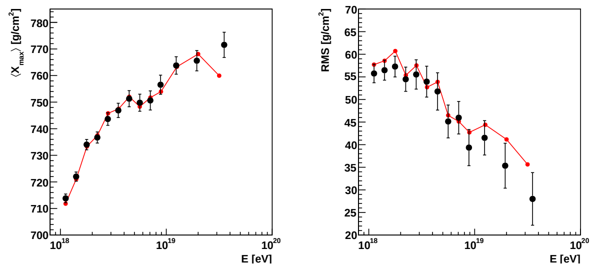

Figure 2: Same as Figure 1, but this time the 4-component model was obtained with a maximum likelihood fit to the Auger X_{max} distributions.

after the Telescope Array SD trigger bias and the agreement is very good, indicating little bias in the $\langle X_{max} \rangle$ between the thrown Monte Carlo tested by Telescope Array and the real Auger data.

Figure 4 compares the widths of the Auger data and the composition mixture used after the Telescope Array SD trigger bias. Again, the agreement is excellent over most energies. The bump in widths of the thrown composition mixture around $10^{18.3}$ - $10^{18.5}$ eV is driven by a deep tail of protons in the CORSIKA sample used to generate the Telescope Array shower library.

The Monte Carlo events were processed using Telescope Array hybrid reconstruction analysis software. Events are simulated and processed by the following procedure:

1. Showers are generated by CORSIKA and the SD trigger response is simulated.

2. The CORSIKA longitudinal shower profile for each shower is fitted to a Gaisser-Hillas function to determine the shower parameters.

3. A shower profile based upon the fitted shower parameters is generated and the TA fluorescence detector response including atmospheric, electronics, and geometrical acceptance is also simulated.

4. The shower geometry is fitted via the fluorescence profile and the shower-detector plane is measured.

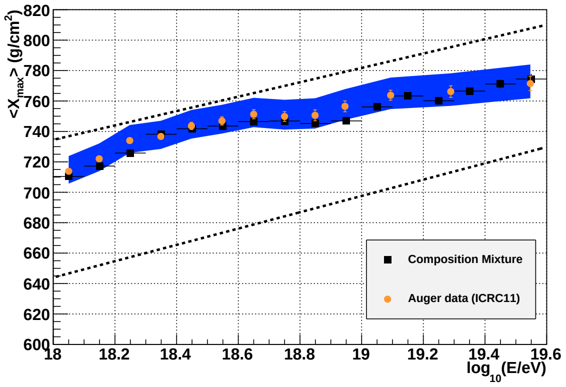

Figure 3: $\langle X_{\max} \rangle$ for the Auger composition mixture after Telescope Array SD trigger bias (black circles) compared to Auger data described in [9]. Dashed lines show QGSJetII proton and iron rails also from [9]. The blue band indicates Auger systematic uncertainties.

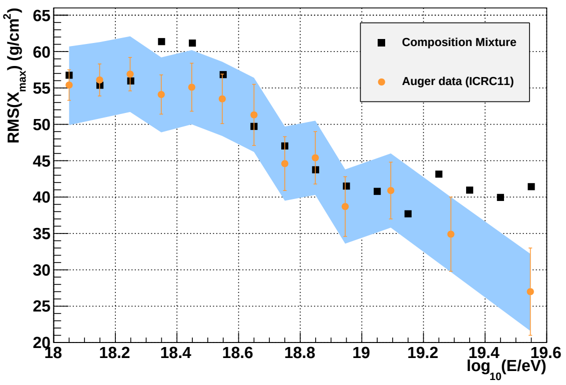

Figure 4: Thrown $X_{\max}$ RMS for the Auger composition mixture (black squares) including Telescope Array SD trigger bias compared to Auger data described in [9]. The blue band indicates Auger systematic uncertainties.

5. A fit to hybrid shower geometry is performed which combines the timing and geometric center of charge of the SD array, with the timing and geometry of the fluorescence detector that observed the event. This step is what makes the event a "hybrid event". If either the SD or FDs fail to trigger in an event, it can not be processed.

6. The shower profile is fitted via a reverse Monte Carlo method where the atmosphere, electronics, and geometrical acceptance of the shower are fully simulated.

The mean $X_{\max}$, after reconstruction of the composition mixture, is shown in figure 5. As has already been shown, the input distribution after SD trigger bias also agrees well with the Auger data. Comparison of the reconstructed widths (RMS) is shown in figure 6. Good agreement with the input distribution and with Auger data is also seen here. We have thus successfully reconstructed the expected features of an input spectrum composed of the given mixture: $\langle X_{\max} \rangle$ intermediate between protons and iron at

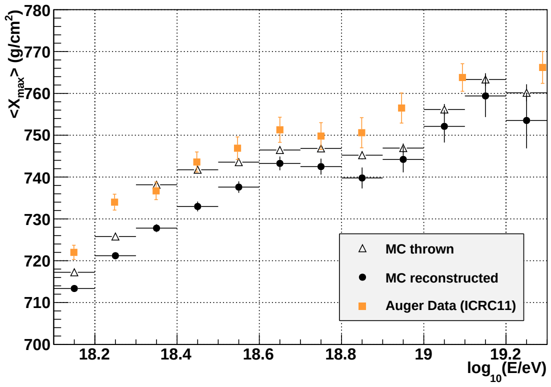

Figure 5: Reconstructed composition mixture $\langle X_{\max} \rangle$ compared with thrown $\langle X_{\max} \rangle$ after Telescope Array SD trigger bias and the most recent Auger composition data presented in [9].

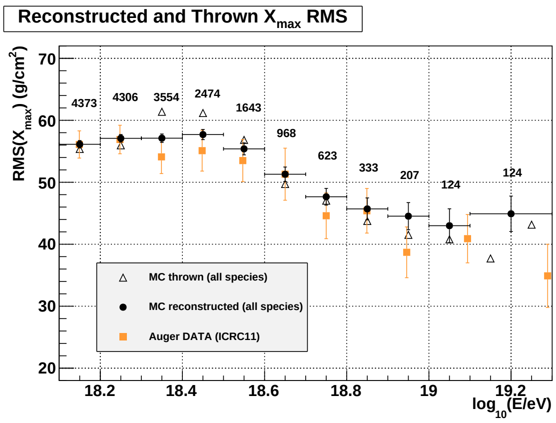

Figure 6: Reconstructed composition mixture $X_{\max}$ widths. The number or reconstructed events is also shown for each bin. Good agreement with the thrown distribution and the Auger data presented in [9] is seen here as well.

the highest energies and widths that narrow as energy increases.

To see if TA hybrid reconstruction techniques can distinguish a spectrum composed purely of protons with one composed according to the Auger mix, a similar analysis was done using the spectrum composed purely of protons. The same spectral shape used for the mixed composition was also applied to the proton spectra and reconstructed using the same techniques. In the top panel of figure 7 $\langle X_{\max} \rangle$ for the reconstructed composition mixture is compared to $\langle X_{\max} \rangle$ for protons (iron reconstruction is included as reference). Over this energy range the mixture can be distinguished from protons and iron. A similar situation is shown in the bottom panel of figure 7 where the widths of the $X_{\max}$ distributions are compared. Above $10^{18.6}$ eV where the widths of the mixture $X_{\max}$ begin to narrow, no issues with Telescope Array reconstruction biases or acceptance preclude distinguishing a pure proton or pure iron spectrum from one that looks like the composition mixture.

Figure 8 shows the overall TA hybrid bias in $\langle X_{\max} \rangle$ for pure proton and for the Auger mix. The bias in both cases is nearly energy independent and it is found to be 11.5 ± 0.9 g/cm^2 for pure protons and 5.2 ± 0.4 g/cm^2 for

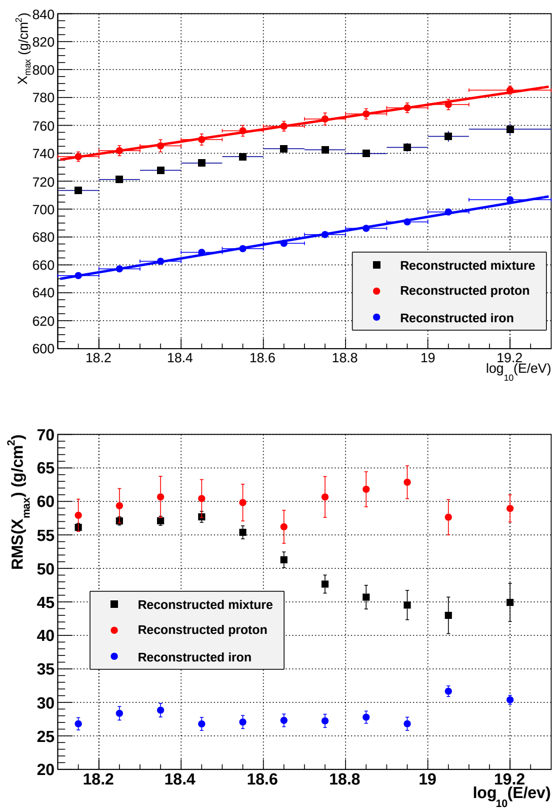

Figure 7: Comparison of $\langle X_{\max}\rangle$ and widths of the reconstructed composition mixture and $\langle X_{\max}\rangle$ and widths of pure proton and pure iron compositions. The three sets are clearly separated in each figure. The mixed composition can be distinguished from protons and iron using TA hybrid reconstruction. The fits to the reconstructed iron and proton $\langle X_{\max}\rangle$ are also shown.

the Auger mix. For this Figure, the total bias calculated for the Auger mix has the Telescope Array surface detector bias removed from it.

3 Conclusions

To begin to understand the apparent differences between Telescope Array/HiRes and Auger composition results, Auger has provided TA with an *ad hoc* model which fits Auger composition measurements. It consists of a 4-component mixture of protons, helium, nitrogen, and iron (the Auger mix) that varies with energy. Telescope Array generated a large Monte Carlo set based on the Auger mix, passed it through the full hybrid reconstruction analysis to obtain the expected $\langle X_{\max}\rangle$ and $X_{\max}$ widths for the Auger mix. In the same way the expectations for pure proton and pure iron were estimated. Figure 7 shows that the difference in the expected $\langle X_{\max}\rangle$ between the Auger mix and the pure proton composition ranges from about 15 g/cm^2 at $10^{18.65}$ eV to about 30 g/cm^2 at $10^{18.85}$ eV.

The expected $\langle X_{\max}\rangle$ and $X_{\max}$ widths for the Auger mix and for the pure proton composition can be compared directly with the real Telescope Array hybrid results. Given the MC statistics generated in this simulation (e.g. 124 events in the energy bin of 10^{19}), and the Telescope Array

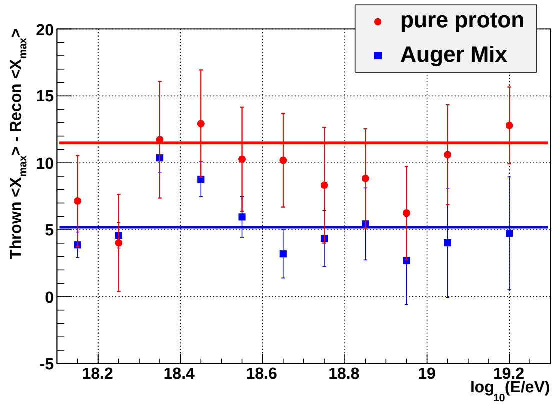

Figure 8: The difference between thrown $\langle X_{\max}\rangle$ and reconstructed $\langle X_{\max}\rangle$ for pure protons and the Auger mix. The total bias in $\langle X_{\max}\rangle$ for the Auger mix is 5.2 ± 0.4 g/cm^2 (with TA SD trigger bias removed) and the total bias for pure protons is 11.5 ± 0.9 g/cm^2.

hybrid reconstruction biases and acceptances over $10^{18.1}$ - $10^{19.3}$ eV, Telescope Array can distinguish between the pure proton composition and the mixed composition provided by Auger (with at least 4 sigmas confidence level at 10^{19} eV). With adequate statistics in the data, Telescope Array will be able to distinguish between pure proton composition and the Auger mix composition.

This Monte Carlo simulation assumes a given atmospheric model that could be slightly different from the one in real data. In this work we have not estimated the systematics due to uncertainties in the atmospheric model used in the Monte Carlo.

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