Measurements of the Composition of Cosmic Rays with VERITAS

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Abstract**. The direct Cherenkov method aims to measure the composition of cosmic rays with improved charge resolution at TeV energies. By exploiting the inherent angular separation and time delay between the Cherenkov radiation initiated by the primary particle and that initiated in the extensive air shower, the charge of the primary particle can be identified. VERITAS, with its 0.15 degree angular resolution and 2 ns time sampling, measures the charge and energy of a selected sample of heavy cosmic rays. We review this new technique and present results from the 2007-2008 season of VERITAS.**

Keywords**: Composition, Direct Cherenkov, VERITAS**

I. Background

The all-particle spectrum of cosmic rays famously follows a power law over many orders of magnitude in energy with a steepening at $\sim 3.5 \times 10^{15}$ eV (the "knee"). Cosmic rays from galactic supernova remnants (SNRs) can explain the spectral break, if you assume a rigidity-dependent acceleration mechanism. Such models predict charge-dependent breaks in the spectra of individual elements [2]. Other models predict changes in composition based on propagation effects [3], changes in acceleration mechanisms [4] [5], new particle physics [6], etc.. See [7] for a recent review. Hence measurements of the elemental spectra from TeV to PeV energies could test whether SNRs indeed fuel the cosmic-ray spectrum up to knee energies.

Recent direct-measurement instruments have attempted to gain greater statistics at higher energies in order to observe the expected breaks in elemental cosmic-ray spectra. By maximizing the total geometric factor with either long duration balloon flights [8] or with large detector areas [9], balloon experiments have been able to measure up to $\sim$ 100 TeV/amu with better than elemental charge resolution. Balloon and satellite experiments become limited by statistics at energies approaching the knee; so in order to cover the knee region, ground-based instruments are required.

Until recently, ground-based instruments have focused on multi-parameter measurements of cosmic-ray air showers. For example, by sampling the muon content and electron content on the ground [10] or longitudinal development of the shower [11], an estimate of the point of maximum development, X_{max}, and therefore the primary charge can be made. These indirect experiments are capable of measuring the composition at PeV energies and beyond, because of their large effective areas. However, they are limited by fluctuations in the extensive air showers, and can therefore, measure the composition of charge groups rather than individual elements.

The H.E.S.S. collaboration recently used a novel technique [12], the direct Cherenkov (DC) method, to measure the composition of cosmic rays from 10 TeV to 100 TeV with unprecedented charge resolution for a ground-based experiment [13]. We employ this method in this work to measure the iron spectrum at similar energies.

II. The Direct Cherenkov Method

First proposed by Kieda, Swordy and Wakely [12], the direct Cherenkov method aims to measure the composition of cosmic rays near the knee with elemental charge resolution. A typical heavy cosmic ray will traverse between $\sim$ 7-18 g/cm^2 before interacting hadronically with a nucleus in the atmosphere. By measuring the intensity of Cherenkov radiation initiated by the primary particle before the strong interaction, the particle species can be identified, because the Cherenkov yield scales with the square of the charge. The Cherenkov radiation emitted by the resulting extensive air shower (EAS) after the strong interaction provides a calorimetric measure of the primary particle's energy.

The difficulty with this measurement lies in separating the direct Cherenkov emission from the Cherenkov light generated by the EAS (hereafter DC light and EAS light, respectively). There are two characteristics of the DC light that differentiate it from the EAS light: emission angle and time of arrival. The direct Cherenkov emission angle will be inherently narrow, because the atmosphere is rarified above the average first interaction height. The DC light also arrives after the air shower light, because it traverses more material before arriving at a detector. An example of a VERITAS event is shown in Figure 1.

Geometric effects combined with the atmospheric profile generate an inherent timing and angular separation of the DC light and the EAS light, such that the angular separation is expected to be on the order of 0.2°, while the time delay will be $\sim$ 2 ns.

III. VERITAS Analysis Methods

VERITAS is a 4 telescope array of imaging atmospheric Cherenkov telescopes. Each telescope employs a 12-m Davies-Cotton reflector to focus Cherenkov radiation onto a camera of 499 photomultiplier tubes

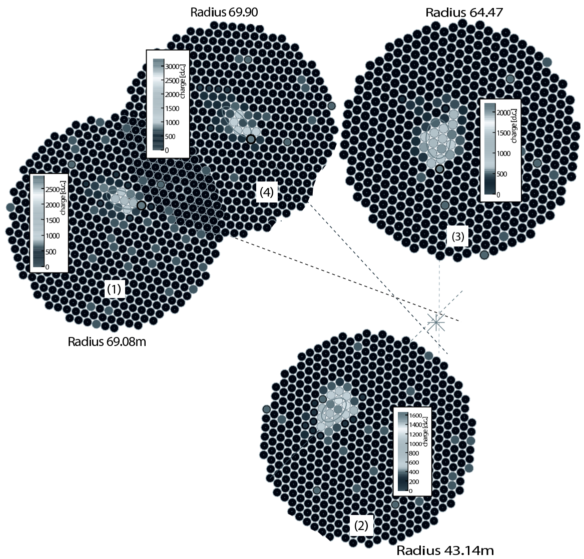

Fig. 1. A candidate event displayed as integrated charge sums on the camera planes. When a telescope is too close to the shower core ($<$50m as in telescope 2), the density of primary Cherenkov photons is too low to produce a signicant DC excess, but at radii between 60 and 70 meters (as in telescopes 1, 3, and 4), the maximum number of DC photons seen by each of the three telescopes is 500 photoelectrons.

(PMT). Each PMT has a field-of-view of 0.15°, while the entire camera views 3.5° of the sky. The PMT signals are digitized at 500 MSPS with flash ADCs (FADCs) and pass through a 3-level trigger. For the status and recent gamma-ray results of VERITAS, see [1] in these proceedings.

As with gamma-ray showers, the longitudinal development of the cosmic-ray extensive air shower manifests itself as an ellipse in the camera plane. The particle's impact parameter and arrival direction can be reconstructed by intersecting the major axes of each ellipse in a multi-telescope event (see Figure 1). The DC events are then selected by applying a geometric cut on the distance between the shower core location and the location of the telescope.

The direct Cherenkov light will be contained in one to three pixels, due to the compact nature of the DC light and VERITAS's angular resolution. Following the method described in [13], the DC light is separated from the EAS light by defining a quality parameter Q for each pixel in the camera image. This Q factor is defined as the ratio of the intensity of a camera-image pixel to the sum of the intensities of the neighboring pixels. We define the DC pixel as the pixel that maximizes Q. This method preferentially selects the brightest and most geometrically separated pixels in an image.

The time development of the shower can also be used to differentiate the DC light from the EAS light. By comparing differences in the rising edges of the PMT traces, the DC light can be separated from the air shower light on a statistical basis [14]. While this does not provide a strong cut for this analysis, further study into the timing effects are warranted.

A. Monte Carlo Simulations

Monte Carlo simulations of ^{56}Fe air showers and direct Cherenkov light production are required to estimate the energy of each shower. Over 500000 ^{56}Fe showers were simulated in 20 energy bins from 3.16 TeV to 316 TeV using CORSIKA 6.720 [15] and the GrISU detector simulation package [16]. The iron showers were simulated with zenith angles between 70-80° and and isotropic azimuthal angles, because the majority of the VERITAS data is taken at 70-80° elevation along with multiple azimuths.

It should be noted that low-mass nuclei cannot be identified using this technique, because they do not generate enough DC light. Therefore, because protons and helium are the most abundant cosmic rays, they are the largest contributors to the background. Thus, it is necessary to simulate proton and helium showers in the same manner as the ^{56} Fe showers. This also provides a convenient check on the simulation parameters. Figure 2 shows that the simulated total Cherenkov light collected in each camera image matches the data.

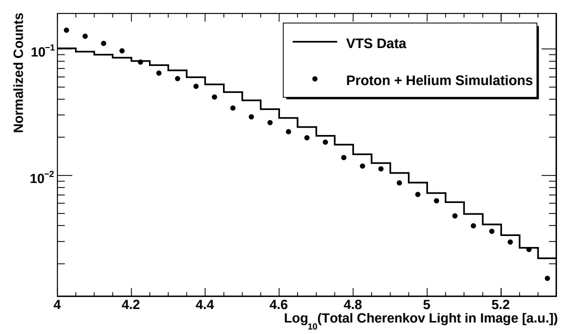

Fig. 2. The total Cherenkov light, as measured at each telescope, is shown here. The dot points represent simulated showers initiated by protons and helium nuclei at energies selected from a power law distribution of $E^{-2.7}$ from 1 TeV to 75 TeV. The showers were scattered in a 750 m square area centered at the center of the area and simulated between 70 and 80° zenith angles. The thick black line represents data from multiple nights at elevations between 70 and 80°. The simulated night sky background rate was adjusted to match the simulations to the data.

B. Energy and Charge Reconstruction

Once the cosmic-ray events have been selected and the DC light identified in each image, the charge can be reconstructed as $Z^* = A\sqrt{I_{DC}}$, where A is a constant that normalizes the mean of the reconstructed charge to the atomic number of iron. The charge resolution is ∼20% when quality cuts are applied.

The sum of the intensity in the camera image depends on the energy of the primary particle as well as impact parameter of the cosmic ray and the offset angle in the camera plane. The energy can, therefore, be reconstructed by filling lookup tables with those parameters and then using spectral deconvolution techniques to correct for the detector response.

IV. CONCLUSIONS

The direct Cherenkov method is a promising approach to measuring the composition of cosmic rays at TeV to PeV energies. VERITAS measurements from the 2007-2008 season are presented in this conference.

V. ACKNOWLEDGEMENTS

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