1 Introduction

The following report describes the analysis for finding the speed of an extensive air shower produced by an ultra-high energy cosmic ray. Not only will this analysis be useful in measuring the speed of cosmic ray showers but also it can help in correcting a bias in the detection instrumentation. As cosmic rays enter Earth’s upper atmosphere, they interact with nuclei, creating secondary particles that share the original particle’s energy. This process of interaction continues and forms a cascade of energetic particles. These cascades are called extensive air showers. By examining the velocity distribution of these air showers, we can figure out the composition of the primary particle.

The flux of these highest energy particles is very low at about $1 \text{ km}^{-2}\cdot\text{y}^{-1}$. Therefore two different types of detectors are used independently to detect these rare particles. The first, a fluorescence detector, detects ultraviolet light when electromagnetic radiation interacts with $\text{N}_2$ molecules in the atmosphere. This optical signal is called a fluorescence. The second detector, a surface detector, employs Čerenkov radiation to decipher the source and intensity of the cosmic ray. Using this hybrid technology, scientists seek to find the enigmatic origin of these particles.

Fluorescence detectors (FDs) at the Pierre Auger Observatory detect electromagnetic air showers produced by cosmic rays interacting with the upper atmosphere. These showers are assumed to travel at the speed of light $c$. Due to the way the detectors are oriented, the geometry of the shower can be measured independently of the speed it travels. Therefore, if the geometry of the shower is well known, then the actual speed of the shower can be calculated. First, I will analyze an experiment where a laser was fired...
upward. The light from this laser causes the atmosphere to fluoresce. FDs detect this fluorescence. A laser beam should travel at the speed of light. I will create an algorithm to find the speed of the laser beam. Once I have accurately found the beam speed, I will apply the same algorithm to measure the speeds of cosmic ray air showers.

1.1 Specifications

In my analysis my goal is to improve the program I write so that I can find a laser beam speed within 0.01 c. After meeting this goal I will move on to analyze cosmic ray air showers. In this study it is assumed that the shower travels at a constant speed and that the speed of light in air differs insignificantly from that in a vacuum. Currently, other studies are developing more accurate descriptions of shower behavior as they travel through the atmosphere and are being implemented into the Auger OFFLINE Framework [1, 2].

1.2 Motivation

Two key factors motivate this project. The first is the search for exotic particles which could possibly include magnetic monopoles [3], heavy quark particles [4], or something else completely different. Other candidates for particles which may generate an optical signal in the FDs are micrometeorites. These extensive air showers might be instigated by a particle traveling slightly slower than c. By measuring the speed of the shower, we can infer the speed of the original cosmic particle, thus giving insight into its composition or mass.

Secondly, this method of calculating speed can be tested with a laser beam such as those produced by the Central Laser Facility (CLF) at the observatory. Figure 1 is a diagram of the Pierre Auger Southern Observatory with the CLF located near the center and the FDs on the perimeter. The lines extending from the FDs show the field of view for each detector. The XLF is a second central laser facility in the process of being built. Each dot represents a surface detector. Since the laser beam is known to be traveling at the speed of light, the FDs must measure c. For each different laser shot, the predicted speed may differ slightly from the speed measured by the FDs, generating an error. Taking the span of these errors for multiple laser events, we can find out if there is a bias in either the instrumentation or the method of analysis.
Figure 1: Layout of observatory. Each dot represents a surface detector. Fluorescence detectors are located on the perimeter with emanating lines indicating each detector's field of view. Near the center are the laser facilities (CLF and XLF) with dashed lines showing the distance to the closest FDs. [5]

2 Method of Analysis

Each FD consists of 440 hexagonal photomultiplier tubes (PMTs) with known zenith and azimuthal pointing directions. As the light from an electromagnetic air shower passes across the array of PMTs, each PMT is triggered at a different time. A photon enters the PMT where it encounters a metal plate. Through the photoelectric effect, this encounter kicks off electrons. The electrons are then focused and more are produced due to secondary emission. Once enough electrons have been gathered, they produce a current. From this current an analog voltage is measured which is then converted to a digital voltage using an analog-to-digital converter (ADC). The program
FDEyeDisplay takes a single event and displays which PMTs were triggered. Also, it shows the ADC counts versus time. Figure 2 shows an example of this program for one event. This event is one of the data sets for a vertical laser track measured by the Coihueco FD. The highlighted pixels represent the PMTs that were triggered. On the right is a graph of ADC counts versus time. Each peak corresponds to a chosen pixel. Bins on the independent axis represent 100 ns increments.

![Figure 2: Left: Filled in pixels represent triggered PMTs. Right: Corresponding ADC traces for each dotted pixel.](image)

The real speed of the shower can be found by analyzing the time development of the extensive air shower across the PMTs and already knowing the three-dimensional geometry of the cascade. Speed, assuming it is constant, can be ascertained by finding the travel times between pixels. The predicted photon detection times are given by the equation

$$t_p = t_o + \frac{d_c}{c} + \frac{d_v}{v}$$

(1)

where $t_o$ is a time offset, $d_c$ is the distance from a point in the shower to the detector, $c$ is the speed of light, and $d_v$ is the distance from the shower point to the shower core (where the shower intersects the ground). At the FD, the light reflects off of a mirror onto the detector, which is composed of an array of PMTs. A simple diagram of this geometry is shown in Figure 3.
In this simple equation for the predicted times, \( v \) and \( t_0 \) remain constant. Therefore, I will calculate a two-parameter fit for Eq. (1), using Root, a data analysis framework. In Eq. (1) all of the distances have a common dependence on the angle \( \theta \). Figure 4 shows the geometry of a laser shot.

Figure 3: Diagram of laser speed components

Figure 4: Geometry of laser shot
After putting the formula for predicted time in terms of one variable, the equation reduces to

\[ t_p = t_o + \frac{L}{c \cos \theta} \left( 1 + \frac{\sin \theta}{1 + \frac{\Delta v}{c}} \right) \quad (2) \]

where \( L \) is the distance from the FD to the CLF, \( \theta \) is the free parameter, \( \Delta v/c \) is the first fit parameter, and \( t_o \) is the second fit parameter. The goal is to find constant values for \( \Delta v \) and \( t_o \) which minimize the standard deviation.

2.1 Testing with CLF

Periodically laser beams are fired from the CLF into the sky. These beams are oriented at specific zenith angles, mostly vertical. Each of the FDs detects the fluorescence stimulated by the laser and records it. Using FDEyeDisplay, I found the times corresponding to the peaks when the light triggered a specific PMT. These data sets are also found in the files named pixel_traces. The centers of the PMTs are separated by approximately 1.5°. Exact values are found in the files named pixel_directions. Figure 5 shows a plot of angle vs. time for a single laser shot event observed independently by 3 of the FDs.
3 Project Progress

3.1 Work to date

The first steps of the project included learning about the Auger project, specifically how the FDs operate [7]. Next, I initiated a literature search on possible exotic particles that could be classified as cosmic rays. These could include magnetic monopoles, massive quark balls, or micrometeorites. This search will continue throughout the project. Next, I started looking at laser data from the CLF using the FDEyeDisplay program. From this data, I developed a simple program to calculate the speed $v$ at which the laser beam traveled.
3.2 Future work

The next steps include performing an error analysis on the calculated velocities. Since the laser beam travels at c, I can calculate the deviation of the real velocity from the predicted. Once a proper statistical error has been ascertained, I will use the same error analysis to examine the speed of a laser beam that is not vertical. Finally, once I can measure the velocity accurately from the laser shots, I will use the same algorithms and apply them to the cosmic ray air showers. If any of the extensive air showers are measured to be traveling at slightly less than c, then these particles are candidates for exotic particles. The possibility of discovering an exotic particle is very slight. However, this process is still beneficial because it can be used to find a bias in the equipment or in the algorithm.

3.3 Timeline

Currently I am writing a program to calculate the speeds of vertical laser shots fired from the CLF. For the rest of the fall semester I will continue to analyze laser shots by developing and debugging this program. By December 5, 2007, I will be done examining laser shots. During the spring semester I will turn my attention toward cosmic ray data. I will apply the same program I used with the laser beams to the air showers. This portion of the project will be finished by March 28, 2008. By the end of the academic year, I will finish the literature search along with writing up the results found throughout this analysis. My Senior Design report will be completed by May 1, 2007.

4 Cost Analysis

Because this is an analysis project, there are no operating or manufacturing costs. I have free access to the data which is located on a computer at the University of Utah.

5 Available Resources

The data for this project has been collected by the four fluorescence detectors at the Pierre Auger Southern Observatory. These records are located on a computer in Utah belonging to the Pierre Auger group at the University of
Utah. I have a personal account on this computer. Also, many programs have already been developed for analysis of the data. A compilation of these programs may be found in the Auger OFFLINE analysis package.

6 Conclusion

The Pierre Auger Observatory observes the highest-energy particles we know of in the universe. By studying the data collected by the detectors, we will one day decipher the enigmatic origin and composition of these mysterious particles. My air shower velocity analysis is a starting point on how to figure out the composition of these ultra-high energy cosmic rays. This specific analysis will probably reveal nothing about new exotic particles. Although, the technique for finding the velocity of a laser beam may prove beneficial to determining a bias in the equipment used to detect air showers. Knowing more about the instrumentation used will help us interpret the data more accurately. Therefore, it will be valuable for me to continue on with this project.

References


