THE COSMIC RAY ENERGY SPECTRUM AS OBSERVED AT THE PIERRE AUGER OBSERVATORY

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Cosmic rays have been observed with energies just beyond $10^{20}$ eV. The cosmic ray flux has been observed to obey a power law with a spectral index close to 2.7, $\frac{dN}{dE} \sim E^{-2.7}$. The Pierre Auger Observatory was built to measure the properties of such cosmic rays. This paper will present the cosmic ray energy spectrum as observed at the Pierre Auger Observatory. The Pierre Auger Observatory uses two methods of detection. One method is from the use of surface detectors. The other method is from the use of fluorescence detectors. For some cosmic ray events, both methods can be used in unison to form a more accurate measurement of cosmic ray properties. When both methods of detection are used, the event is called a hybrid event. The Pierre Auger Observatory uses different software to reconstruct each type of event. Surface detector event reconstruction was used to produce the energy spectrum presented in this paper.
Dedicated to Meghan and Skye.
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Chapter 1

Introduction

1.1 History

Cosmic rays are particles that bombard the Earth from space. They come in many different forms. They can be atomic nuclei of elements such as, but not limited to, Hydrogen, Helium, or Iron. They can also be elementary particles and electromagnetic radiation. Such cosmic ray particles bombard the Earth with observed energies of upwards of $10^{20}$ eV.

Victor Hess is credited with the discovery of cosmic rays. Hess used an electroscope to measure ambient radiation in different environments. He found that radiation increased as he ascended into the atmosphere in a hot air balloon, which was surprising because it was thought at that time that the radiation measured by electroscopes at ground level came from radioactive decay in the Earth’s crust. Because of this, it was thought that radiation levels should
decrease with altitude. Because of this discovery Hess won a Nobel Prize in 1936.

Just after Hess was awarded the Nobel Prize for his discovery of cosmic rays, Pierre Auger discovered what is now known as extensive air showers, or EAS. Initially in a lab in Paris, Auger discovered that bursts of radiation would be detected simultaneously in detectors that were separated by about 20 meters at ground level. Auger then took his experiments to the Alps where he separated his detectors by 200 meters at the same elevation. He found once again that these detectors would go off at the same time. Because of the coincidental hits, Auger concluded that the particles that set off the detectors, which were separated by hundreds of meters, were the result of a parent collision higher up.
in the atmosphere. What Auger saw was part of a ‘shower’ of particles. Upon further investigation, Auger and his colleagues determined that there existed natural particles with energies up to $10^{15}$ eV. Auger in a 1939 article in *Reviews of Modern Physics* wrote:

One of the consequences of the extension of the energy spectrum of cosmic rays up to $10^{15}$ eV is that it is actually impossible to imagine a single process able to give to a particle such an energy. It seems much more likely that the charged particles which constitute the primary cosmic radiation acquire their energy along electric fields of a very great extension [1].

It was then established that some particles in nature had much higher energies than those resulting from radioactive decay in the Earth’s crust, which had energies of only a few MeV. Auger discovered cosmic rays with energies as high
as $10^{15}$ eV. In 1962, Linsley discovered a cosmic ray event with an energy of $10^{20}$ eV [2]. Scientists now had to explain the origin of particles detected with energies as high as $10^{20}$ eV. A new mystery came from these discoveries: where do these high energy particles come from? Since the particles had energies much higher than radioactive decay products, and their flux increased with altitude, the conclusion was made that the particles had to come from extra-terrestrial sources. But how can particles from outer space have such high energies?

1.2 Top-Down and Bottom-Up Mechanisms

There are two basic types of models that address this issue: the top-down models and the bottom-up models. The bottom-up models are models where particles get a huge boost in energy from astrophysical objects such as radio galaxy lobes or active galactic nuclei. Some of the first acceleration models were proposed by Enrico Fermi [4]. The most promising top-down models are models where ultra high energy (above $10^{18}$ eV) particles are created from the decay or annihilation of super massive particles, such as super heavy dark matter, or the decay of some sort of topological defect [3]. Such interactions are similar to $e^+e^-$ decay into hadrons: two or more off-mass-shell quarks and gluons are produced and then create a QCD cascade. This results in energetic photons [3]. Lorentz-invariance violation is also a possible explanation for what is observed [3].
1.2.1 Fermi acceleration

In the second-order Fermi acceleration, charged particles get reflected by randomly moving magnetic fields, or ‘mirrors’, in interstellar space. Fermi claimed that, on average, particles would get increases in energy through these interactions. It was later shown that supernova remnant shocks would be a rather efficient way of accelerating particles because the magnetic fields in supernova remnant shocks are no longer moving randomly. This type of acceleration is known as first-order Fermi acceleration. The problem with such ‘shocks from supernovae’ models is that they can only account for energies that are much less than energies as high as $10^{18}$ eV. Fermi acceleration by shock waves gives us an upper limit on how much energy can be given to a particle of charge $Ze$ [5]:

$$E_{\text{max}} \approx \beta c \times Ze \times B \times L$$  \hspace{1cm} (1.1)

where $B$ is the magnetic field strength, $L$ is the characteristic size of the shock region (for example, $L$ could be the diameter of a pulsar), and $\beta c$ is the shock velocity ($\beta \approx 0.01$ for supernovae). Figure 1.4 is a plot by Hillas [6] where known quantities of $B$ and $L$ for given astronomical objects are plotted alongside a band that corresponds to an energy of $10^{20}$ eV for a proton primary (solid line) and an iron nucleus primary (dashed line). ( Corrections to this work have been done by Medvedev [7], since many cases of acceleration will involve radiative losses.) Objects that lie outside of this band are not capable of accelerating particles to such a high energy.
Figure 1.3: First and second order Fermi acceleration. From[16].
Figure 1.4: The original Hillas plot. From [6].

From this plot, we do indeed see that supernova remnants (SNR) are not plausible sources of acceleration up to $10^{20}$ eV. We also see that some of the more likely candidates for such large accelerations, such as active galactic nuclei, galactic clusters, and radio galaxy lobes, are extragalactic. With these results, it needs to be asked whether or not particles accelerated by such objects can reach us through intergalactic space.

### 1.3 The GZK Cutoff

Suppose a proton, for example, gets accelerated by some process outside of our galaxy and gets sent on its way to us on Earth. The proton has to get through intergalactic space to get to us. Throughout this space there are CMB
(Cosmic Microwave Background) photons, which interact with energetic ($\approx 5 \times 10^{19}\text{eV}$, enough to excite a $\Delta$ resonance.) protons via:

$$p + \gamma_{CMB} \rightarrow \Delta^{+} \rightarrow p + \pi^{0}$$  \hspace{1cm} (1.2)

and also

$$p + \gamma_{CMB} \rightarrow \Delta^{+} \rightarrow n + \pi^{+}$$  \hspace{1cm} (1.3)

$$\&$$

$$p + \gamma_{CMB} \rightarrow p + e^{+} + e^{-}$$  \hspace{1cm} (1.4)

Because of these interactions, the proton will lose energy. Through the interaction, momentum must be conserved, hence:

$$E_{\pi}m_{\pi} = E_{p}m_{p}$$  \hspace{1cm} (1.5)

and thus through each interaction(1.2) the proton loses $m_{\pi}/m_{p} \approx 15\%$ of its energy. (Interaction (1.4) has an energy loss of $\approx .1\%$, which results in the proton still being above photopion production threshold.) It must now be asked how long a proton will travel before it will interact with a CMB photon. To a CMB photon, the proton looks like a cylinder with length $R$ and cross section $\sigma$. The probability of interaction in the distance $R$ is thus $\sigma R n$, where $n$ is the number density of photons in the universe. Therefore, the mean free path for one interaction is:

$$\lambda = (\sigma_{\pi n_{CMB}})^{-1}$$  \hspace{1cm} (1.6)
Currently, the number density of photons in the universe is $n_{CMB} \approx 400 \text{cm}^{-3}$[8]. The cross section is of the order of 100 $\mu b$. We thus have a mean free path of approximately 10 Mpc. The distance scale for energy loss is:

$$L_{\rho\pi} = (E/\Delta E)(n_{CMB}\sigma_{\rho\pi})^{-1}$$

Interaction length and energy loss length is shown in figure 1.5 (from [9]). The maximum propagation distance for a $10^{20}$ eV proton is approximately 100 Mpc. We should thus see a sharp cutoff in the flux of cosmic rays with energies around $10^{20}$ eV, since such particles can only reach distances of around 100 Mpc. For particles that we do detect, whether or not they be extragalactic in origin, we now need to explain how they are detected.
Chapter 2

Modern Detection Methods

2.1 Air Showers

As previously discussed, Pierre Auger first discovered extensive air showers (EAS) in the 1930’s. He found that particles detected on the surface of the Earth came from a parent collision higher up in the atmosphere. After the initial collision, many more interactions take place in the atmosphere, resulting in an EAS. Assuming a proton primary, the first collision with a particle in the air will result in many pions, some kaons, and a leading baryon. All of these particles get created from the energy of the primary. Since the primary was so energetic, the first few generations of secondaries also have huge amounts of energy. These secondary particles will usually interact in very much the same way as the primary. As the shower develops, more and more particles are created. Eventually, all of the primary’s energy will get spent into creating new
particles and bremsstrahlung. The newly created particles will mainly end up decaying into photons, neutrinos, electrons, and muons. This secondary particle creation and decay is shown in figure 1.2. We can see from the figure that there are three components to an EAS: the muonic, hadronic, and electromagnetic components. Throughout the shower, the transverse momentum of the secondary particles is minimal. Because of this, the central component, the hadronic component, will define the shower core. The hadronic shower core will be of high importance since it will tell us what direction the primary came from.

At the point where the energies of the newly created particles are not high enough to interact again and create more particles, there are a maximum number of secondary particles. This point is called \( X_{\text{max}} \). Knowing the exact point, or depth, where there is a maximum number of particles, helps us understand what kind of particle the primary cosmic ray was. (see figure 2.1.) We can see in the figure that the two curves, representing protons and photons, have different values for \( X_{\text{max}} \). With all of the different interactions in the atmosphere, giving rise to different kinds of particles, there are different methods of detection. Two methods of detection, as used at the Pierre Auger Observatory, will be discussed.

### 2.1.1 Fluorescence Detection

When a cosmic ray hits a particle in the upper atmosphere, ionizing radiation results. Such radiation excites particles to higher energies, and almost
immediately the particles emit some of that energy in the form of photons. This process is called scintillation, or fluorescence. There is some controversy as to which term is most accurate for describing what happens in the atmosphere, but the astrophysics community has decided to stick with the term fluorescence. Hence the term, fluorescence detection. Such radiation that is emitted from these interactions is called, etymological disagreements notwithstanding, air fluorescence. In fluorescence detectors, photons of these wavelengths are reflected off mirrors onto an array of photomultiplier tubes, or PMTs (see figure 2.2). The PMTs then output signals to computing equipment, sending information on the time of arrival of the signal and the amount of light that was collected. From this information, many properties of the initial cosmic ray can be reconstructed, including $X_{\text{max}}$ and the primary’s initial energy. To the detector, an EAS appears as a spot of light that moves across the sky at close to the speed of light, firing off a line of PMTs as it travels. (The amount of light collected from this quickly moving spot is proportional to the energy deposited by
2.1.2 Surface Detection

The use of surface detectors in cosmic ray experiments is beneficial since such detectors are low maintenance and operate on a 100% duty cycle. A surface detector is a Cerenkov light detector which is filled with very pure water and equipped with an array of PMTs that detect Cerenkov light that results from charged, energetic particles traveling through the detector. The detectors are also lined with reflective material in order to guarantee that the Cerenkov light is uniformly spread out and detected. As the light is detected by the PMTs, electrical signals are produced that are analyzed in order to reconstruct the proper-
Figure 2.3: A representation of the longitudinal shower development. The maximum is defined to be $X_{\text{max}}$. From [22].

Figure 2.4: An image of the SDP as seen by fluorescence telescope. The cylinders on the ground represent surface detectors. From [23].
ties of the particle(s) that passed through it. Such surface detectors are used to measure the lateral profile of the shower, where the fluorescence detectors are used to measure the longitudinal development of the shower. Measurements from fluorescence detection and surface detection act as orthogonal measurements of the shower. Many experiments have been constructed that use either surface detectors or fluorescence detectors. The Pierre Auger Observatory is the first to use both methods of detection in one experiment. This design helps solve some of the problems that result from only using one method of detection.
Chapter 3

The Pierre Auger Observatory

3.1 The Detectors

The Pierre Auger Observatory has two different sites that will eventually be utilized fully: the northern site (Auger North) in southeastern Colorado, USA and the southern site (Auger South) on the Pampa Amarilla plain in Argentina. Currently, the northern site is undergoing the process of being developed, and the southern site is up and running. Auger South covers an area over 3000 km² in Mendoza province, Argentina. The surface detectors in use at Auger South are in a grid where each surface detector is spaced approximately 1.5 km from each other. Along the perimeter of this 1600 water tank grid there are four fluorescence detecting ‘eyes’ (see figure 3.1). I will now discuss how the Pierre Auger Observatory utilizes both methods of detection discussed here (surface and fluorescence) in order to help understand the cosmic ray phenomenon.
3.1.1 Fluorescence Detectors at the PAO

The fluorescence detectors at the PAO detect light that results from the excitation and de-excitation of nitrogen molecules in the atmosphere when they are hit by electrons that formed in the EAS. This fluorescence is produced in the near-ultraviolet and visible part of the electromagnetic spectrum. Since the detectors are usually several kilometers from the shower, the light emitted from the shower can be absorbed by the atmosphere. Therefore, this kind of detection is limited to clear, moonless nights, which drastically reduces its duty cycle. When conditions are favorable, such fluorescence light becomes experimentally significant at ground level, kilometers from the shower core, for energies above $10^{17}$ eV [10].

Figure 3.1: The grid of surface detectors with the fields of view of the four ‘eyes’. From [18].
In each eye, there are 6 telescopes with a field of view of 30° in azimuth and 29° in elevation [11]. This gives us a field of view of 180° for each eye. Light from the shower enters the eye through one of six apertures, as seen in figure 3.2. The light is then reflected off an 11 m² mirror onto a camera placed at the focal surface. Each camera has 440 pixels. Each PMT pixel has an observable area in the sky of (1.5°)². As previously mentioned, the most important use of the fluorescence detector at the PAO is the measurement of the longitudinal development of the EAS. As the shower travels through the night sky, the fluorescence camera outputs data from the PMT pixels. From this data, \( X_{\text{max}} \) is easily determined. Also, the energy deposited into the atmosphere is estimated from the output of the pixels. The problem with this is that the derived energy from the longitudinal profile covers only what can be seen in the field of view of the detector (see figure 2.3. The colored tails of the profile represent what can’t be seen by the detector.) To extend the longitudinal profile outside the field of view of the detector, and get an accurate reconstruction of the primary’s
energy, a simple fit of the longitudinal profile of air showers is used, called a Gaisser-Hillas function [25]. A typical one-dimensional Gaisser-Hillas function is:

$$N_e(X) = N_{\text{max}} \left( \frac{X - X_0}{X_{\text{max}} - X_0} \right)^{X_{\text{max}} - X_0} \exp\left( \frac{X_{\text{max}} - X}{\lambda} \right)$$

(3.1)

where $X$ is the atmospheric depth, $N_{\text{max}}$ is the shower size at maximum, $\lambda$ is the mean free path, and $X_0$ is the depth of first interaction. When this fit is used, the shower maximum must be in the field of view of the detector. Once this fit is successfully made, the electromagnetic cascade energy can be estimated. For the hybrid nature of the PAO, the lateral profile obtained from surface detector data also needs to be reconstructed.

3.1.2 Surface Detectors at the PAO

Each surface detector station at the PAO is a cylindrical tank with a diameter of 3.6m and height of 1.2m. Each tank is filled with 12,000 liters of pure, deionized water. Three PMTs are attached to the top of the detector in order to measure the Cerenkov light that results from energetic particles that pass through the detector. The inner surface of the tank is lined with a diffusive-reflective material called Tyvek, in order to spread out the Cerenkov photons. When a shower occurs, particles from the muonic and electromagnetic components form what is called a ‘pancake’, as seen in figure 3.4. From the timing of the detector hits, the arrival direction of the primary is determined. The distribution of these particles along with what is called a lateral distribution function
(LDF) are needed to reconstruct the primary’s energy.

The lateral distribution function is a function, \( S(r) \), of distance from the core of the shower, fitted to the signals in the water tanks. Showers that develop higher up in the atmosphere produce flat LDFs and showers that develop lower produce steeper LDFs. Also, different primaries will give different shapes for the shower and different values for \( X_{\text{max}} \). At about 1 km, the signal is independent of the primary mass and shower fluctuations. Therefore, the quantity \( S(r) \) for \( r = 1000 \text{m} \) is used to build the lateral profile of the shower at the Auger Observatory [26]. Because of this, the first step in the reconstruction is to estimate \( S(1000) \).
Figure 3.4: The front ‘pancake’ of an EAS. From [15].
3.2 Hybrid Events

Hybrid events are events that consist of shower measurements from both techniques of detection. This method of detection is one of the things that make the PAO different from any other cosmic ray experiment before it. The two methods of detection see EAS in complementary ways. This results in many advantages over surface only and fluorescence only experiments. The hybrid method of detection results in a more accurate reconstruction of the shower development. The hybrid method also provides a way to calibrate surface detector only measurements, which have much higher statistics. Such reconstructions and measurements are handled by special software developed for the PAO, called the offline software framework.
Chapter 4

The Offline Software Framework of the Pierre Auger Observatory

4.1 Introduction to the Framework

The framework is implemented in C++ and comprises three principal parts: modules, an event structure, and a detector description, as depicted in figure 4.1. The modules are sequenced and assembled through an XML file. The event structure is capable of relaying data from one module to one another, accumulating all reconstruction information. The detector description provides access to information that describes the configuration and performance of the observatory and the atmospheric conditions at the time of the event. Such a system is flexible enough to support usage by a large number of physicists over the course of 20 years, which is the projected lifetime of the experiment.
4.1.1 Fluorescence Event Reconstruction

The PMTs used in the fluorescence detector create digitized signals using ADCs at a frequency of 100MHz. This yields signal traces with pulse divisions of 100ns. In order to get an accurate reconstruction of the longitudinal development of the shower, certain properties of the atmosphere must be known. Light can be Rayleigh-scattered or Mie-scattered in the atmosphere. The properties of the air and of Mie-scattering aerosols in the atmosphere are measured and taken into account by certain equipment at the observatory. Such properties are measured by the Horizontal Attenuation Monitor (HAM), the Aerosol Phase Function monitors (APF), and the Lidar systems. Each eye has such equipment. In the middle of the array of surface detectors there is the Central Laser Facility (CLF), which consists of a laser that produces pulses of linearly polarized UV light. This polarized light beam is visible to each eye. This allows measurement of the properties of the atmosphere at that time. This information is then able
to be recorded for later use in the reconstruction of the shower.

4.1.2 Surface Event Reconstruction

The PMTs used in the surface detectors pass signals to an FADC (Flash Analog to Digital Converter), where they are digitized to 40MHz. The signal is then processed for different triggers. Initially, the data is stored as a T1. Then onboard software determines whether or not the signal was at the T2 level, which is a determination whether or not the signal came from an EAS. If so, the signal is sent to the Central Data Acquisition System (CDAS). The third level is a trigger that is an array level trigger, where it is checked that multiple stations have been hit. The fourth level is a physics selection trigger. The fifth level trigger is a quality trigger where events are checked based on the cleanness of the event. That is, this trigger removes events that occur too close to the edge of the array. Once these conditions have been met, the LDF can be calculated, and the event can be reconstructed.

The reconstruction of each surface event happens in five stages. First, a calculation is done in order to estimate S(1000). An approximation of the shower core position is also made. The next two stages of the reconstruction fit the candidate stations for S(1000) and the shower core. An analytic estimation of the shower-front curvature and axis is made during the last two stages of the reconstruction [27].
4.1.3 Hybrid Event Reconstruction

Hybrid events are reconstructed with an initial calibration of the surface and fluorescence detectors, which turns data into physical quantities. Once that occurs, a pulse finding algorithm is used to process the traces recorded by the fluorescence detectors. Then the shower plane is determined, along with the eye that saw it. After that, the image of the shower as it traverses the pixels in the fluorescence detector is compared to where the surface detectors found the impact point. This results in a complete geometrical fit of the plane. Finally, the fluorescence light profile recorded by the telescope is converted to the actual amount of energy deposited at a given atmospheric depth along the shower axis [12].
Chapter 5

The Measured Energy Spectrum

5.1 Introduction

Once the energy of each observed event is reconstructed, we can make an energy spectrum. Experiments since the beginning of cosmic ray research have built a store of many recorded events. The flux as a function of energy from such experiments is plotted in figures 5.1 and 5.2.

From these graphs of the flux, we see a steeply-falling power law, where the power shifts a bit in three regions. The shifts are called the ‘knee’ at about $10^{15}$ eV and the ‘ankle’ at about $10^{18.5}$ eV.

5.1.1 Energy Spectrum from the PAO

The trigger system for the experiment has been designed to allow surface detectors to operate at a wide range of primary energies, with full efficiency for
Figure 5.1: The cosmic ray energy spectrum as observed by various cosmic ray experiments, as shown. From [13].
Figure 5.2: Another energy spectrum. The yellow region is attributed to mostly solar cosmic rays. The blue region is attributed to galactic cosmic rays. Extra-galactic cosmic rays are mostly in the purple region. From [14]
cosmic rays above $10^{19}$ eV. The events used to produce figures 5.3 and 5.4 were taken from hybrid events from 2005 - 2007. The energies, as reconstructed with the offline software framework surface reconstruction package, are plotted. This gives us the spectra in figures 5.3 and 5.4. In figure 5.4, the spectrum was plotted and with a fitted line with a slope of -2.7, which is consistent with other experiments [28].

5.1.2 Conclusion

From figures 5.3 and 5.4, we can see the same shape of the energy spectrum as measured by the POA as we see in figures 5.1 and 5.2, which were taken from experiments other than the experiment at the Pierre Auger Observatory. From figure 5.4 we can also see that at $10^{19}$ eV we have a flux of about $10^{-24.7}$ (m$^2$ sr
Figure 5.4: Flux as a function of energy. The fitted line has a slope of -2.7, which is consistent with values of the spectral index found from experiments other than the PAO experiment [28]. The data was analyzed with the offline package and plotted with the ROOT graphical tool.
sec GeV$^{-1}$. Comparing this to figure 5.2, we can see that the data taken and presented in this paper is consistent with the other cosmic ray experiments. Data taken from the PAO is consistent with the other cosmic ray experiments.
Bibliography


