Extensive Air Shower High Energy Cosmic Rays (II)

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ABSTRACT

A recently published article in Science\(^1\) by the Pierre Auger Laboratory, has helped pinpoint the source of ultrahigh energy cosmic rays, which are the most energetic particles known in the universe. The sources found indicate support for the “active galactic nuclei” theory, which is that the ultra-high energy (UHE) cosmic rays come from super massive black holes found at the centers of galaxies. The Pierre Auger Observatory\(^2\) records the extensive air showers through an array of 1,600 particle detectors placed 1.5 km apart in a grid spread across 3000 square kilometers. In light of this latest development the author wishes to discuss extensive air showers.

1. Introduction

This article is in continuation of a series of compiled work on cosmic ray physics which the author has undertaken as member of the GRAPES3 Collaboration, at Tata Institute of Fundamental Research, Mumbai.

The ultrahigh energy cosmic ray flux is small and is a steeply falling power law in energy. Thus experiments at ultrahigh energies need a large detector volume. Consequently, the primary cosmic ray particles cannot be observed directly, since they interact in the upper atmosphere and induce extensive air showers with of the order of \(10^{16}\) particles for a \(10^{19}\) eV primary. The properties of the original cosmic ray particle, such as arrival direction and energy, have to be inferred from the observed properties of the extensive air showers.
shower. The mass of the primary cosmic rays at the energies above $10^{17}$ eV are also found using several techniques. The mass measurements, firstly, involving the elongation rate, secondly those involving the fluctuations in the depth of maximum, thirdly from the muon density measurements, fourthly the mass estimates from the lateral distribution function and lastly from the thickness of the shower disk. All these different methods of measuring the mass give different answers and the conclusions are dependent, in all cases, upon the model calculations that are assumed.

The elongation rate is the term used to describe the rate of change of depth of shower maximum with primary energy. This parameter is useful for organizing and describing the data and calculations. In the literature we find many plots of the measurements of the depth of maximum together with the predictions from a variety of model calculations. These plots indicate that if the certain models are correct, one might infer that the primaries above $10^{19}$ eV are dominantly protons but that others are indicative of a mixed composition.

Further insight is expected to come from the magnitude of the fluctuation of the position of depth of maximum, $X_{\text{max}}$. If a group of showers is selected within a narrow range of energies, then fluctuations about the mean of $X_{\text{max}}$ are expected to be larger for protons than for iron nuclei.

A known fact is that a shower produced by an iron nucleus will contain a greater fraction of muons at the observation level than a shower of the same energy created by a proton primary. Many efforts to derive the mass spectrum of cosmic rays have been attempted using this fact over the full range of air shower observations. However, although the differences are predicted to be relatively large (on average there are ~ 70% more muons in an iron event than a proton event), there are large fluctuations and, again, there are differences between what is predicted by particular models.

The rate of fall of particle density with distance from the shower axis provides a further parameter that can be used to deduce the mass composition. Showers with steeper lateral distribution function (LDFs) than average will arise from showers that develop later in the atmosphere, and vice versa. A detailed measurement of the LDFs of showers produced by primaries of energy greater than $10^{17}$ eV was made at Haverah Park.

The particles in the shower disk do not arrive at a detector simultaneously, even on the shower axis. The arrival times are spread out because of geometrical efforts, velocity differences, and because of delays caused by multiple scattering and geomagnetic deflections. The first particles to arrive (except very close to the shower axis) are the muons as they are scattered rather little and geometrical effects dominate. This type of study will be considerably extended with the Pierre Auger Observatory in which the photomultipliers within each water tank are equipped with 25 ns flash ADCs.

An incoming primary particle collides at a great height with an oxygen or nitrogen nucleus, giving rise to a shower of mesons and nucleons which continue towards the Earth approximately along the projected axis of the incoming particle. This central region around the axis is usually called the 'core' of the shower. Further nuclear disintegrations are produced by these axial particles, giving rise to more mesons and nucleons, constituting the nucleon cascade. In the initial and subsequent collisions, the neutral pi-mesons produce decay into high energy gamma rays which then initiate photon-electron cascades. Some of the charged pi-mesons decay into mu-mesons which form a penetrating non-interacting component.

An extensive air shower is not a special type of cosmic ray phenomenon. Over the last 70 years, physicists have studied cosmic rays with energies in excess of $\sim 10^{14}$ eV by using the earth's atmosphere itself as part of the
detection equipment. This technique takes advantage of the fact that interaction between high-energy cosmic rays and the air produces a correlated cascade of secondary particles. The process begins with the collision of the primary cosmic ray with a nucleus near the top of the atmosphere. This first collision typically produces more than 50 secondary particles, a majority of which are pi-mesons (generally called pions). Pions come in three different flavors: positively charged, negatively charged and neutral. All pions are unstable, but the charged pion is relatively long-lived and will most probably collide with another nucleus before decaying. The subsequent collisions are similar in nature to the primary collision. This process then leads to a cascade of particles which is referred to as a “hadronic shower”. One third of the pions produced are neutral. The neutral pions are very short-lived and will almost all decay into a pair of photons (gamma rays) before interacting with nuclei in the atmosphere. The photons interact with the nuclei in the air to produce electron-positron pairs, which in turn will produce photons via the “bremsstrahlung” process. This cascading process leads to the formation of an “electromagnetic shower”. The hadronic shower itself continuously produces neutral pions and thus initiating secondary electromagnetic showers along its path. Conventionally, both types of cascades are called “extensive air showers”, EAS.

Development of cosmic-ray air showers

Figure 1
2.1 Study of the Extensive Air Shower

Extensive air showers were discovered in the 1930’s by French physicist Pierre Victor Auger. As an EAS develops into the atmosphere, more and more particles are produced. A small fraction of the kinetic energy of the primary particle is converted into mass energy. The remaining kinetic energy is then distributed over the shower. The process of multiplication continues until the average energy of the shower particles is insufficient to produce more particles in subsequent collisions. This point of the EAS development is called the “shower maximum”. Beyond the maximum the shower particles are gradually absorbed with an attenuation length of ~ 200 g/cm.

Two properties of the shower maximum to mention are the number of particles and the slant depth. First, at maximum, an EAS typically contains ~1-1.6 particles for every 1GeV (10^9 eV) of energy carried by the primary cosmic ray, and secondly, the average slant depth at which the shower maximum occurs, varies with the energy of the primary cosmic ray.

The slant depth represents the amount of material penetrated by the shower at a given point in its development and is denoted by the symbol “X”. The value of X is calculated by integrating the density of air from the point of entry of the air shower at the top of the atmosphere, along the trajectory of the shower, to the point in question. Hence the units of X are density (gm/cm^3) multiplied by length (cm). To feel it, an air shower traveling along an exactly vertical, downward trajectory traverses ~ 1000 gm/cm^2 in reaching sea-level. This value of 1000 gm/cm^2 can be interpreted as an atmospheric pressure. Hence an inclined shower will traverse more than 1000 gm/cm^2 to reach the sea-level. Using the above convention the depth of the shower maximum is denoted by “X_max” whose measured value can be used as a measure of the composition and energy of the primary cosmic ray. The hadronic interaction length in air for protons is about 70 gm/cm^2 and shorter for heavier nuclei. This fact implies that EAS induced by heavier elements tends to suffer its first interaction higher in the atmosphere, and so have shallower X_max than showers of the same energy initiated by a lighter element.

For air showers with energies in excess of 10^{15} eV, the shower maximum penetrates to half the vertical atmospheric depth or more. There is also a sufficient number of particles in the cascade such that the remnant of the shower can be detected as a correlated event by an array of individual particle detectors on the ground. The threshold (the lowest energy detectable by an instrument) of such a “ground array” depends on the altitude of the array. Generally, it is difficult to measure cosmic rays with energies below 10^{14} eV with ground arrays. An early example of a ground array is the Haverah Park array operated by the University of Leeds and more recent one is the Akeno Giant Air Shower Array (AGASA) operated by University of Tokyo. The ground arrays sample the lateral density profile (explained in the next subsection) of the shower as it hits ground with no direct information on the longitudinal development (defined in next subsection) of the shower; in particular there is no measurement of X_max. One method to supplement a ground array is to install a muon array and the other one is to implement an air Cerenkov array with the ground array.

Along with an underground muon array we can measure the composition of the primary particle with a ground array. An example of such a combination used to search for very high energy gamma rays was the Chicago Air Shower Array Michigan muon Array (CASA-MIA) array which operated in 1989-1997 at the U.S. Army Dugway Proving Ground. As the extensive air shower traverses the earth's atmosphere the relativistic charged particles in the pancake emit Cerenkov light. Cerenkov
light is the electromagnetic equivalent of a sonic boom. The particles in a typical air shower are all traveling just below the speed of light in vacuum. In air, however, they are actually traveling faster than the speed of light in the medium. The result is that they emit light called Cerenkov light.

This leads to two different methods that can be used to detect the passage of an extensive air shower: one can look for the particles in the pancake directly, or one can look for the Cerenkov light generated by the particles in the atmosphere. The figure below illustrates both techniques.

On the left is an Air Cerenkov Telescope (ACT): These are large mirrors that focus the light generated by the air shower onto an array of photomultiplier tubes (PMTs), which form an image of the air shower. Properties of the image are used to distinguish between air showers generated by gamma-ray primaries and nuclear primaries. Though very few particles may survive to the ground, the Cerenkov light will reach the ground. Thus, ACT can detect lower energy cosmic rays than extensive air showers arrays. However, since they are optical instruments they can only operate on clear moonless nights and can only view a small piece of the sky at a time.
On the right is an Extensive Air Shower array (EAS array): An EAS array has traditionally been composed of a sparse array of plastic scintillators. The scintillators detect the passage of charged particles that travel through them. They are very inefficient detectors of the gamma rays in the EAS. Since gamma rays outnumber electrons and positrons by a ratio of roughly 4:1 and the scintillator covers less than 1% of the total area of the array, traditional EAS arrays have rather high energy threshold. Unlike ACTs, EAS can operate under all conditions, day or night and can view the entire overhead sky continuously.

2.2 Experimentally Studied EAS Properties

The EAS can be studied at the surface, beneath the earth, and at various mountain elevations. The experimentally determined quantities are

a) The lateral distribution function, i.e. the particle density as a function of distance from the shower axis of the charged particles in the EAS or the lateral structure of the shower at different depths in the atmosphere.

b) The lateral distribution of Cerenkov light produced by the EAS particles in the atmosphere.

c) The lateral distribution functions of the muons generated by the pions and kaon decays in the EAS.

d) The longitudinal development of the shower as it proceeds downwards through the atmosphere can be determined in an indirect way from the study of the lateral distribution. The time distribution of particles arriving at the surface as well as the Cerenkov light pulse rise time and width also carry information about the longitudinal development of the shower. Although detection of Cerenkov light at the surface can be studied, this is somewhat model dependent. The only direct way to study the longitudinal development of EAS is to observe the
atmospheric fluorescence associated with the passage of particles through the atmosphere.

e) For each shower one determines its direction, its longitudinal development and lateral spread of different shower particles, one can infer from these measurements the energy and nature of the cosmic ray initiating the shower. The shower particle swarm moves close to the speed of light and arrives at the observation level as a curved pancake of relativistic particles. Timing of the pancake is used to find the direction of the incident primary. The maximum of the shower cascade can be determined by the direct observation of the longitudinal development of the cascade using either fluorescent light or Cerenkov radiation.

The composition inference is indirect and involves detailed simulations which require knowledge of physics of high energy particle interactions and the characteristics of the shower detectors. The mass dependence can be inferred from the position of the depth of shower maximum in the atmosphere, or from the muon content of the shower. Muons, once they are produced through decay of pions or kaons etc. do not interact very much with air, and measuring their total number can provide an estimator of the mass $A$, because heavy nuclei interact higher up in the atmosphere where decay of unstable particles can be more important relative to their interactions.

3. Electromagnetic Cascade

In a first approximation, the EAS generated by a hadron interacting in the atmosphere behaves as if only electromagnetic processes are important. Let us then study the nature of purely electromagnetic cascade process. Assume that an incident photon of energy $E_0$ traverses distance $R$ before creating an electron-positron pair. Each lepton of the electron-positron pair has half of the initial energy on the average. After traveling another distance $R$, each electron will bremsstrahlung and produce a photon of average energy $E_0/4$. At a distance $R_n$ into the shower, there will then be $2^n$ particles created, each with an average energy $E_0/2^n$. This multiplicative process continues until the average energy of the particle drops below some energy $E_c$, called the critical energy. The critical energy is defined as the energy below which the dominant energy loss is by ionization rather than by bremsstrahlung.

The shower reaches its maximum development when the average energy of the cascade particles equals the critical energy. The total number of photons and electrons at the shower maximum is then given by total energy $E_0$ divided by the critical energy $E_c$. The number of particles at shower maximum $N_{max}$, on the other hand, equals $E_0/E_c$ and is linearly dependent on the primary energy. This general result applies to hadronically initiated showers as well. Longitudinal development of EAS initiated by gamma-rays or electrons can be explicitly calculated by solving the relevant transport equations by Monte Carlo simulations.

The development of electromagnetic cascades is described using an “age” parameter $s$. This parameter is formally introduced in the solutions of the diffusion equations describing the shower development. The age parameter in some literature indicates how near one is to the start of a cascade. For $s<1$, the shower would be classified as ‘young’ as it is still capable of further development. Old showers would be those beyond their maximum of development $s>1$. When $s=2$, the number of particles remaining in the shower has dropped below 1. The relation is expressed as

$$d \ln N(t)/dt = \lambda(s)$$
where \( N \) is the shower size, \( t \) is the distance along the shower in terms of radiation lengths and \( \lambda(s) = 0 \) when \( s = 1 \). Hillas\(^1\) has given approximate expressions for the longitudinal development of electromagnetic showers.

\[
N_e = (3.1/\gamma)9\exp[t(1 - 1.5 \ln s)]
\]

where \( N_e \) is the number of electrons in the shower, \( t \) is the depth into the shower in radiation lengths;

\[
y = \ln \left( \frac{E_0}{E_c} \right)
\]

where \( E_0 \) is the incident energy and \( E_c \) is the critical energy; and

\[
s = 3/(1+2y/t)
\]

is the shower age.

4. Hadronic Shower Development

Hadronic showers can be considered to be a superposition of individual electromagnetic showers produced by pi-zero decays and fed by the hadronic core. Thus such showers do not have a well-defined age parameter. At atmospheric depths beyond shower maximum, there is little influence from the hadronic core, and the shower behaves like an electromagnetic cascade. However, the shower rise and the position of shower maximum are dependent on the details of the hadronic interaction and the nature of the primary particle.

The depth of the first interaction depends on the hadronic interaction length which is 70 gm/cm\(^2\) for protons and approximately 15 gm/cm\(^2\) for iron nuclei at PeV energies. For proton interactions, roughly half of the initial energy is lost in the first interaction. The subsequent position of shower maximum, \( X_{\text{max}} \), is strongly dependent on the position of the first interaction and the energy loss which occurs there. The position of the depth of shower maximum, \( X_{\text{max}} \), depends on the product of the inelastic cross-section \( \sigma_{\text{inel}} \) and their elasticity \( K \), defined by

\[
K = \frac{(E_0 - E')}{E_0} \frac{E_0 + M_N}{M_N}
\]

where \( E_0 \) is the incident energy, \( E' \) is the energy of the nucleon after collision, and \( M_N \) is the target mass in energy units. On the other hand, the individual hadronic sub showers produced by heavy nuclei will be lower in energy by a factor \( E_0/A \) where \( A \) is the atomic number assuming that the nucleus fragments in the first interaction. Then the sub showers will have shallower \( X_{\text{max}} \) distributions and smaller fluctuations than the protons. These details depend on the hadronic interaction model assumed.

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Reference