Measurement of the Mass Composition of the Highest Energy Cosmic Rays with the Pierre Auger Observatory

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Contents

Abstract

The origin of ultra high energy cosmic rays is one of the big unsolved questions in Astrophysics today. Knowing the mass composition of these cosmic rays would help to determine information about both their propagation and acceleration. The Pierre Auger Observatory was built to gather more information and more statistics than any previous cosmic ray detector ever built. In this thesis, I will detail my method of extending the current Pierre Auger mass composition information by using surface array parameters as a proxy for the depth of shower maximum, an established mass indicator.

Declaration of Originality

I, Alexander Edward Hervé, certify that this work contains no material which has been accepted for the award of any other degree or diploma in any university or other tertiary institution and, to the best of my knowledge and belief, contains no material previously published or written by another person, except where due reference has been made in the text.

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Introduction

Since the discovery of cosmic rays at the beginning of the twentieth century, some of the most important properties of these energetic particles such as the origin, production mechanisms and mass composition, still remain a mystery. Specifically unsolved are the properties of Ultra High Energy Cosmic Rays (UHECRs), defined as those with an energy above 10^{18} eV, which exceed by several orders of magnitude the maximum energy attainable in the most recent man-made accelerators such as the Large Hadron Collider.

The flux of cosmic rays is strongly dependent on primary energy decreasing down to 1 particle per km^2 per century for energies around 10^{20} eV. The observation of UHECRs with such a low flux is possible through the detection of the so-called Extensive Air Showers (EAS). The interaction of an extremely energetic cosmic ray with an atmospheric nucleus induces the development of a cascade of secondary particles which can be observed from the ground with an appropriate instrument. Because of the extremely low flux, large instrumented surfaces are necessary to study the most energetic cosmic rays. The Pierre Auger Observatory is at present the largest detector constructed to study UHECRs.

The Pierre Auger Observatory was conceived as a hybrid detector designed to study with high significance the energy spectrum, arrival direction distribution and mass composition of UHECRs. The hybrid concept, in which the Pierre Auger project is a forerunner, implements a combination of the two most successful techniques previously used in the study of high energy cosmic rays. A Surface Detector (SD), composed of over 1600 water Cherenkov stations, samples the secondary particles at ground level, while a Fluorescence Detector, made up of 27 telescopes, registers the longitudinal development of the shower by collecting the faint fluorescence light emitted by atmospheric nitrogen molecules previously excited by cascade particles crossing the atmosphere.

The flux suppression above around 10^{19} eV postulated by Greisen, Zatsepin and Kuzmin due to the interaction of UHECRs with the Cosmic Microwave Background Radiation, has been recently observed with high significance by the Pierre Auger Collaboration. In addition, a related breakthrough reported by the Collaboration has been the observation of correlations between the direction of nearby Active Galactic Nuclei and the arrival directions of the highest energy cosmic rays.

Determining the mass composition of UHECRs is crucial for the interpretation of these results, i.e. the energy spectrum and the distribution of arrival directions, as well as for an appropriate understanding of the acceleration mechanisms and the possible sources. In this thesis a method to extract the mass composition of UHECRs is presented. The technique is based on the slope of the lateral spread of particles (the lateral distribution function or LDF) measured by the SD of the Pierre Auger Observatory. As will be shown, the slope of the LDF is a very useful mass-sensitive parameter, well correlated with the distance to the depth of shower maximum. Another technique, using the asymmetry of the LDF at 1000 m for composition measurements, is also discussed as well as extensive studies of the characteristics of the LDF.

This thesis is divided into 10 chapters.

- **Chapter 1** A brief overview of the history of cosmic rays, including possible origin and sources as well as propagation.
- **Chapter 2** A description of the phenomenology of EAS and a summary of the most used techniques developed for detecting them.
- **Chapter 3** Previous and current cosmic ray detectors and their significant results are mentioned, leading into a summary of the Pierre Auger Observatory. Results from the current generation of cosmic ray detectors are discussed.
- **Chapter 4** The current status of mass composition measurements are detailed: both the results and the methods of obtaining the measurements.
- **Chapter 5** The method of using the slope of the (LDF) to characterise the mass composition is detailed.
- **Chapter 6** Results from extensive studies of the characteristics of the LDF.
- **Chapter 7** A proposed new LDF and results of tests and comparisons with the old LDF.
- **Chapter 8** Updating the old method of characterising mass composition using the new LDF and investigating systematics in the method.

- **Chapter 9** The procedure of characterising the mass composition using the asymmetry of the LDF at 1000 m is presented.
- **Chapter 10** Final concluding remarks.