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

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Contents

Abstract	i
Declaration of Originality	ii
Acknowledgements	iii
Introduction	1
1 Cosmic Rays	4
1.1 Discovery of Cosmic Rays	4
1.2 Energy Spectrum	7
1.3 Mass Composition	10
1.4 Origin & Sources	11
1.4.1 Top-down Mechanisms	11
1.4.2 Bottom-up Mechanisms	12
1.4.3 Possible Sources	16
1.5 Propagation	17
1.5.1 Magnetic Fields	17
1.5.2 Energy Losses	19
1.5.2.1 GZK Limit	19
1.6 Anisotropy	21
2 Extensive Air Showers	22
2.1 Components of Extensive Air Showers	24
2.1.1 Hadronic Component	25
2.1.2 Electromagnetic Component	26
2.1.3 Muon Component	27
2.2 Heitler Model	27
2.2.1 Gaisser-Hillas Profile	29
2.3 Atmospheric Fluorescence and Cherenkov Light Production . .	29
2.4 Measuring EAS	31

2.4.1	Ground Arrays	32
2.4.2	Fluorescence Detectors	34
2.4.3	Hybrid Detection	35
3	Cosmic Ray Detectors	37
3.1	Previous and Current Cosmic Ray Detectors	37
3.1.1	Volcano Ranch	37
3.1.2	Haverah Park	38
3.1.3	SUGAR	39
3.1.4	Yakutsk	39
3.1.5	Fly's Eye	40
3.1.6	AGASA	41
3.1.7	HiRes	41
3.1.8	Telescope Array	42
3.2	Pierre Auger Observatory	42
3.2.1	Communications and CDAS	44
3.2.2	Offline Software Framework	44
3.2.3	Surface Detector	46
3.2.3.1	Detector Design	47
3.2.3.2	Station Triggers	48
3.2.3.3	Calibration	50
3.2.3.4	Geometry Reconstruction	52
3.2.3.5	Energy Reconstruction	53
3.2.4	Fluorescence Detector	57
3.2.4.1	Detector Design	57
3.2.4.2	Calibration and Atmospheric Monitoring	59
3.2.4.3	Triggering and Electronics	60
3.2.4.4	Geometry Reconstruction	61
3.2.4.5	Energy Reconstruction	64
3.2.5	Hybrid Event Reconstruction	68
3.2.6	Upgrades to the Detector	70
3.3	Current Measurements from Cosmic Ray Detectors	72
3.3.1	Energy Spectrum	72
3.3.2	Anisotropy	77
3.3.2.1	Large Scale Anisotropies	78
3.3.2.2	Correlation Studies	80
4	Mass Composition	84
4.1	Optical Detector measured shower properties used for mass composition	84
4.1.1	The depth of shower maximum X_{max}	84

4.1.2	Fluctuations in X_{max}	88
4.2	Surface Array measured shower properties used for mass composition	88
4.2.1	Muon Content	89
4.2.2	Rise time $t_{1/2}$	92
4.2.3	Lateral Distribution Function	92
4.2.4	Azimuthal asymmetry	93
4.2.5	Other observables	94
5	Using Lateral Distribution Function Parameters for Mass Composition	96
5.1	Method	97
5.2	Elongation rate from SD	103
5.2.1	Comparing elongation rates at different zenith angles	106
6	Studies of the current Lateral Distribution Function	109
6.1	Studies of saturation using simulated events with unsaturated traces	109
6.2	“Total LDF” method	112
6.3	Issues with functional form and possible solutions	114
6.4	Concluding remarks on this study	119
7	Proposed new Lateral Distribution Function	120
7.1	New functional form and fixing the parameters	121
7.2	Testing new functional form	123
7.2.1	Finding a parameterisation for the β and γ parameters of the new LDF	125
7.3	Conclusion	136
8	Update of SD elongation rate using new LDF form	137
8.1	Low energy bias	138
8.2	Updated method	140
8.3	Investigating the effect of the Molière radius	149
8.4	Solving the inclined shower problem	154
8.5	Systematic errors in the calibration method	158
8.6	Concluding remarks on the method	160
9	S_{1000} Asymmetry and its relation to mass composition	161
9.1	Asymmetry in extensive air showers	161
9.1.1	Sources of azimuthal asymmetry	162
9.1.1.1	Geometrical asymmetry	162

9.1.1.2	Shower evolution and atmospheric attenuation	166
9.1.1.3	Other causes	169
9.1.2	Effects of asymmetry in shower reconstruction parameters	169
9.2	Testing the asymmetry using MC showers and the “Total LDF” method	169
9.3	Measuring the asymmetry ratio using real data	173
9.4	Applying the asymmetry method to real data and comparing with MC showers	177
9.5	Concluding remarks	183
10	Conclusions	186
A	β vs DX plots for the linear and quadratic $\sec \theta$ correction to X_{max}	188
A.1	Linear correction	188
A.2	Quadratic correction	191
B	Core Shift graphs for simulated data	195
C	E/L ratio plots for other opening angles	197
D	Bibliography	204

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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My friends and family have been a constant source of support over the course of my studies. I would like to thank my parents in particular, Jill and Tony. Their encouragement and support to allow me to continue what I wanted to do helped get me through to this stage of my studies.

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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 signifi-

cance 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.