Acronyms

This is a list of alphabetically sorted acronyms used throughout this work.

CR	*Cosmic Ray*	5
DAQ	*Data Acquisition*	7
EAS	*Extensive Air Showers*	8
FD	*Fluorescence Detector*	7
GAP	*Giant Array Project*	10
SD	*Surface Detector*	7
PAO	*Pierre Auger Observatory*	7
UHECR	*Ultra High Energy Cosmic Ray*	5
UV	*ultra violet*	8
WCD	*Water Cherenkov Detector*	7

Contents

Todo list

remove todos

add pdf hyperref keywords

Introduction

git

Part 1: Cosmic rays and extensive air showers

Contents

*Cosmic Ray*s (CRs) are particles of extraterrestrial origin that travel very close to the speed of light. Their relativistic kinetic energy pc far exceed their rest mass mc^2. In particular, *Ultra High Energy Cosmic Ray*s (UHECRs) are typically defined as CRs with energies exceeding $1\,\mathrm{EeV} = 10^{18}\,\mathrm{eV}$ [P6]. These microscopic fragments are direct witnesses to the most violent processes known to date, and as such of great interest to researchers. Not only do they hold the key to understanding particle interactions at extremely high energies and small scales, but can also improve our understanding of the cosmos, and the universe at large scales.

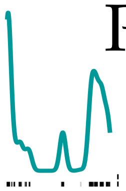
It follows a discussion of the source mechanisms and origins of cosmic rays in Section 1.1 and Section 1.2. Various scenarios of CR creation at different sources are highlighted. In Section 1.3 we describe the transport of CRs through the cosmos from source to observer (i.e. earth). We finish with Section 1.4, where the interactions between CRs and the upper atmosphere that give rise to large cascades of secondary particles are explained.

1.1 Sources of cosmic rays

1.2 Origin of cosmic rays

1.3 Propagation of cosmic rays

1.4 Extensive Air Showers



Part 2: The Pierre Auger Observatory

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Contents

The *Pierre Auger Observatory* (PAO) is the (by area) largest scientific experiment in the world. It consists of an array of 1660 *Water Cherenkov Detectors* (WCDs), which form the *Surface Detector* (SD), and 27 fluorescence telescopes, that make up the *Fluorescence Detector* (FD).

With a region spanning roughly 3000 km^2 it offers a unique possibility to observe UHECRs at the tail-end of the CR energy spectrum with an unprecedented accuracy and precision.

We begin this chapter in Section 2.1 by formulating open questions that the PAO aims to answer. Design details for the FD and for the SD are given in Section 2.2 and Section 2.3 respectively. After a discussion on the local *Data Acquisition* (DAQ) process and the centralized event detection in Section 2.4, we finish by detailing the procedure of the event reconstruction and higher level analysis in Section 2.5.

2.1 Science Goal and Open Questions

The flux of cosmic rays with energies exceeding the ankle, 5×10^{18} eV, is very low, and measures on average 6 events per km^2 yr [P7]. It is evident that one needs a large detector and a lot of time in order to make statistically relevant statements about the physics of UHECRs. Altough only one of the initially planned two data taking sites came to reality [for white paper see P2], the Pierre Auger observatory has been be a world-leading experiment in terms of measured exposure from the beginning of DAQ in January 2004 [P3], and will continue to yiel results until decomission after 2030 [C1].

Many insights, such as the existence of the CR dipole discussed in Section 1.2, have been gathered from Augers event database as a consequence. Still, a plethora of mysteries remain. It follows a list of, in no particular order, important missing links of information that motivate not least this thesis, but the continued effort and daily work done by the Auger collaboration.

2.1.1 Flux supression at highest energies

2.1.2 Validity of shower simulations

2.1.3 Exotic events

Photon showers

Neutrino showers

GZ effect

2.2 The Fluorescence Detector

The Fluorescence Detector of the PAO is a set of 27 reflector telescopes tuned to detect faint sources of *ultra violet* (UV) light. More specifically, the aim of the FD is to observe UV-emission of *Extensive Air Showers* (EAS). However, since the solar irradiance (120 W/m^2 @ 200 nm–400 nm [P5]) and even the lunar irradiance (16 nW/m^2 @ 180 nm–300 nm [P1]) in the UV-band far outshine the emission of UV-light by cosmic rays (), the FD can only operate in the astronomical night during third to first quarter moon. This consequently drops the duty cycle to approximately 20%.

2.2.1 Telescope and camera design

2.2.2 Calibration of measurements

Drum calibration

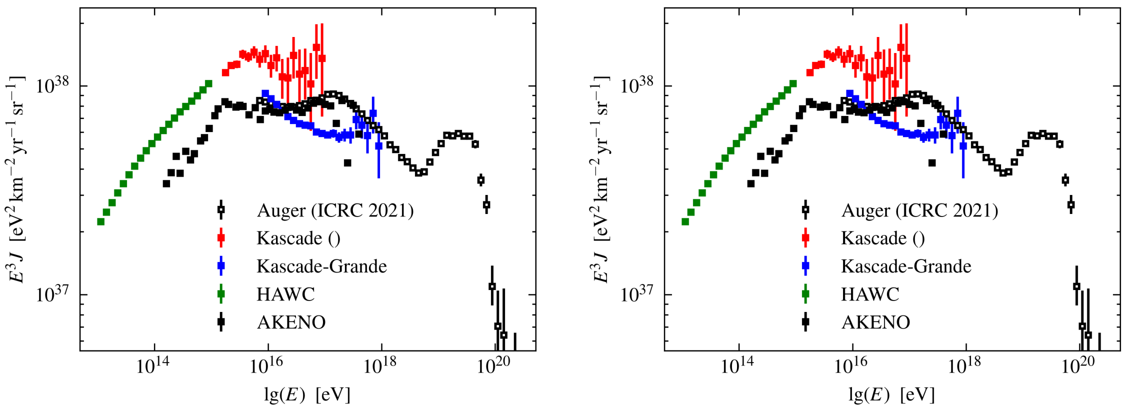
XY-scanner

2.3 The Surface Detector

roughly mention design, duty cycle

2.4 Central Data Acquisition System

2.5 $\overline{\text{Off}}\underline{\text{line}}$ and Event Reconstruction



(a) **(b)**

Figure 2.1: (b) asdasd (b) asdasd

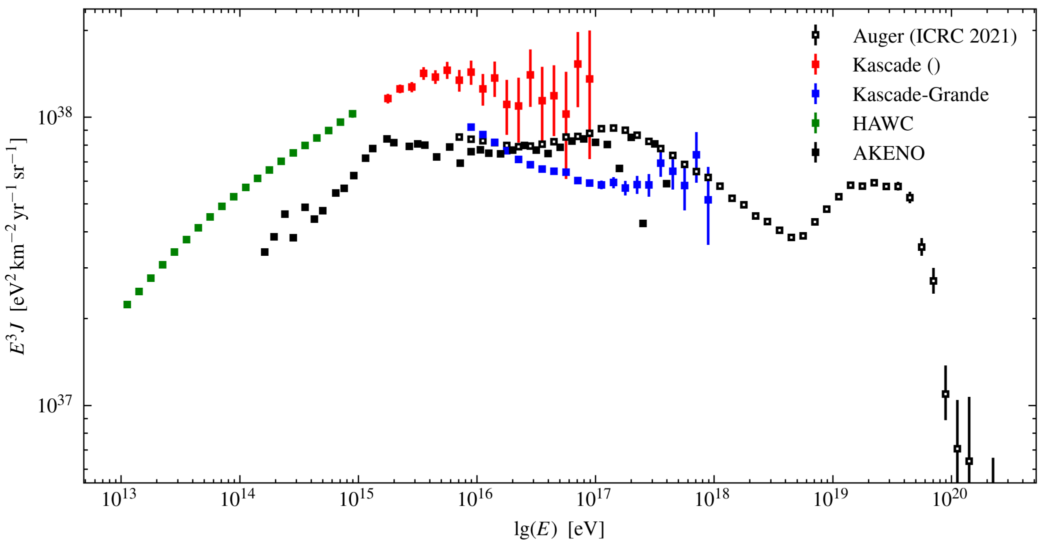


Figure 2.2: asdasdasdasd

Bibliography

The Pierre Auger observatory hosts an internal database of papers. These typically short reports serve to accelerate the exchange of knowledge within the collaboration, and are called *Giant Array Project* (GAP) notes. Since they contain information that is not freely accessible outside the Pierre Auger collaboration, they are, among other internal information listed in a special category with the prefix ***A***. Similarly, sources from personal correspondence are grouped with the prefix ***C***. Physical references, also containing official publications by the Pierre Auger collaboration, can be found with label ***P***. All other references are indexed under the label ***O***.

Personal Correspondence

[C1] Antonella Castellina. “Outcome of the Finance Board”. Dec. 2023.

Physics References

[P1] J. Lean. “Contribution of Ultraviolet Irradiance Variations to Changes in the Suns Total Irradiance”. In: *Science* 244.4901 (Apr. 1989), pp. 197–200. ISSN: 1095-9203. DOI: 10.1126/science.244.4901.197.

[P2] Danilo Zavrtanik and P. Auger Collaboration. “The Pierre Auger Observatory”. In: *Nuclear Physics B-Proceedings Supplements* 85.1-3 (2000), pp. 324–331.

[P3] J Abraham et al. “Properties and performance of the prototype instrument for the Pierre Auger Observatory”. In: *Nuclear Instruments and Methods in Physics Research Section A: Accelerators, Spectrometers, Detectors and Associated Equipment* 523.1-2 (2004), pp. 50–95. DOI: https://doi.org/10.1016/j.nima.2003.12.012.

[P4] M. Ave et al. “Spectrally resolved pressure dependence measurements of air fluorescence emission with AIRFLY”. In: *Nuclear Instruments and Methods in Physics Research Section A: Accelerators, Spectrometers, Detectors and Associated Equipment* 597.1 (Nov. 2008), pp. 41–45. ISSN: 0168-9002. DOI: 10.1016/j.nima.2008.08.052.

[P5] Martin Snow et al. “Absolute Ultraviolet Irradiance of the Moon from the LASP Lunar Albedo Measurement and Analysis from SOLSTICE (LLAMAS) Project”. In: *Cross-Calibration of Far UV Spectra of Solar System Objects and the Heliosphere*. Springer New York, 2013, pp. 227–253. ISBN: 9781461463849. DOI: 10.1007/978-1-4614-6384-9_8.

[P6] Rafael Alves Batista et al. “Open questions in cosmic-ray research at ultrahigh energies”. In: *Frontiers in Astronomy and Space Sciences* 6 (2019), p. 23.

[P7] Francesco Fenu and P. Auger Collaboration. “The cosmic ray energy spectrum measured with the Pierre Auger Observatory”. In: *Advances in Space Research* 72.8 (2023), pp. 3531–3537. ISSN: 0273-1177. DOI: https://doi.org/10.1016/j.asr.2023.06.020. URL: https://www.sciencedirect.com/science/article/pii/S0273117723004581.

Supplementary Information

Proofs and Derivations

Additional Figures

Tabulated Data

Additional Content

2.6 Approximating the upper limit of the UV irradiance of an EAS

In the following, we estimate the UV irradiance, I_{UV}, or Wattage deposited per area, from fluorescence light stemming from an extensive air shower. To illustrate that telescopes need to be incredibly sensitive to observe this phenomenon, we assume fantastic to unrealistically good conditions for the UV light yield and related parameters. This thus results in a very optimistic upper limit to I_{UV}.

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this

Consider a cosmic ray with energy $E_0 = 10^{20}\,\mathrm{eV}$ impinging almost vertically ($\theta = 15°$) on the upper atmosphere. We assume the behaviour of the particle cascade resulting from the deeply inelastic scattering processes of the primary particle is completely determined by the Heitler-Matthews model (see). We then arrive at the following expression for the atmospheric depth (height), at which the EAS reaches its maximum in multiplicity:

$$X_{\mathrm{max}} = 600\,\mathrm{g/cm^2} \qquad (\approx 20\,\mathrm{km\ above\ earth\ surface}) \tag{2.1}$$

of the primary particle behaves purely Heitlerian, we arrive at the following value for the atmospheric depth (height) at which the shower reaches its maximum in multiplicity:

N_2 is the 2P(0,0) transition [P4], which lies at $\lambda = 337.1\,\mathrm{nm}$.