Extensive Air Showers
Peter K.F. Grieder

Extensive Air Showers

High Energy Phenomena
and Astrophysical Aspects

A Tutorial, Reference Manual and Data Book

Volume I
Cover

Left: Photograph of the original KASCADE air shower array at Karlsruhe, Germany, showing part of the 252 huts, distributed over an area of 200 by 200 m, that house the combined unshielded (all charged particle) and shielded (muon) detectors, and the huge central hadron calorimeter. The latter measures 320 m$^2$, is 11.5 nuclear interaction lengths deep and consists of nine layers of lead, iron and concrete. In addition the experiment includes major muon tracking facilities. It was designed to study galactic cosmic rays at energies around the spectral knee region (PeV). In 2003 the experiment had been extended to KASCADE-Grande, covering an area of 700 by 700 m and an energy range up to 1 EeV. The experiment could then study the galactic-extragalactic transition region of the cosmic radiation. It was shut-off at the end of March 2009 (Courtesy of Forschungszentrum Karlsruhe, Germany).

Right: The Crab Nebula (catalogue designation M1, NGC 1952, Taurus A) in our own Galaxy is the remnant of the supernova SN-1054, discovered by Chinese astronomers in the year 1054 AD. I have chosen this picture as a symbolic representative of a galactic research object, reflecting the aims of the KASCADE project to study the galactic cosmic radiation. Recently, old documents had been found in European monasteries where the event SN-1054 is mentioned, thus confirming the Chinese observation. The Crab Nebula spans about 11 light-years across (3.4 pc) and is at a distance of approximately 6, 500 ± 1, 600 ly (2 ± 0.5 kpc) from our location. A Pulsar (rotating neutron star) is in its center. Both objects are emitters of gamma rays and are intensely studied by gamma ray astronomers (Courtesy of ESO).
To
Estelle
and our
Family
This book grew out of a personal need to carry out my work more efficiently. It was in the 60s when I began to develop the first highly structured air shower simulation program and was carrying out extensive air shower simulations on an almost industrial basis. The primary aim at that time was to study the systematics of hadronic interactions at the highest energies in conjunction with experimental air shower and accelerator data. This goal remains to date but today the determination of the primary mass, its energy dependence and questions related to the origin, acceleration and propagation of the most energetic cosmic rays are in the foreground.

The results obtained with the ever growing shower model that eventually grew into the program system named ASICO (Air shower SImulation and COrrelation), which later on became CORSIKA, were so manifold and rich, and covered essentially the full scope of air shower observables that it became necessary to build a library of experimental data for comparison and efficient analysis work; this was the beginning of this book. As the library grew it became evident that it could be of interest to a broader community, active in air shower research. A natural consequence was to add theoretical and tutorial sections to the various chapters, and to expand the book to a comprehensive reference manual for researchers that can also be used as a text book for the advanced student.

The data presented in these two volumes are not an all-inclusive collection. In view of the very large number of experiments that were carried out by so many research groups throughout the years it became unavoidable to take a selection for the presentation here, to compile the data and summarize results. Emphasis was therefore given to the historically as well as the contemporarily scientifically relevant information and data. The fast evolving field of ground based high energy gamma ray astronomy, which employs air shower detection techniques (air Cherenkov as well as particle detection), is only touched on the side, mostly in connection with wide-angle large aperture atmospheric Cherenkov detector arrays. Today, the field of gamma ray astronomy is essentially a separate discipline of its own, yet it remains closely related to cosmic ray and air shower research.
Readme

Organization of the Book: Extensive air showers consist of a superposition of extremely complex processes that involve different fundamental interactions and many aspects of particle physics, cosmic ray physics and astrophysics. Most observables are functions of many variables and parameters and all observables are more or less coupled with each other. This complexity makes it difficult to break up the vast contents of this book into self contained chapters that can be studied separately and in an easily digestible form. I have carefully reflected on how to structure the presentation of the contents of this book and I fully realize that subject oriented sectioning can be done in different ways. A clear structure is of basic importance for the reader and student. No matter how the structuring is carried out, a consequence of the complexity of the subject is that much cross referencing between the chapters is required to link the topics properly. Moreover, an extensive subject index is needed to navigate successfully through the volumes. Both of these requirements are fulfilled and I hope that the reader will be satisfied with the presentation and contents.

The book is divided into two parts that are in two separate volumes. Part I deals mainly with the basic theoretical framework of the processes that determine an air shower. Included are, after the general introduction chapters that describe the shower detection techniques and the basic shower reconstruction procedure using directly accessible shower parameters, followed by a summary of the relevant hadronic, electromagnetic and weak interactions and the cascade formation processes. Subsequently a detailed discussion of the longitudinal, lateral and temporal shower development, and an outline of the complexity and interrelationship of the indirectly observable process and parameters follows. Part I ends with a summary of ways and means to extract information from air shower observations on the primary radiation and presents a compilation of data of our current knowledge of the high energy portion of the primary spectrum and composition.

Part II contains mainly compilations of data of experimental and theoretical nature as well as predictions from simulations of individual air shower constituents, i.e., spectra and distributions of separate components in showers. Also included are chapters dedicated exclusively to special processes and detection methods. These comprise optical atmospheric Cherenkov and fluorescence phenomena that offer special observational windows and have proven to be successful alternatives to particle measurements because they yield three-dimensional insight into the shower process, and radio emission that may possibly develop into a useful future method of detection. I have also included a brief chapter that deals with correlations of shower observables, one that exposes the technique of air shower simulations, and the inevitable chapter on miscellaneous topics. Part II ends with a compilation of definitions and relations, and several appendices that offer useful information. For the benefit of the reader, extensive cross referencing is used that links different yet related topics for rapid access. The extensive subject index at the back of each volume covers both volumes.
Overviews: With the exception of Chap. 1 (Introduction, Facts and Phenomenology) each chapter is preceded with a brief *Overview* that summarizes the contents and offers directions where to find related topics that some readers may expect to find in the chapter but are discussed elsewhere.

Comments on Observation Levels: It will be noticed that sometimes different atmospheric depths or altitudes are specified for a particular site in different chapters and sections, and for different data sets of the same site. This reflects the actual situation in the literature. Most authors do not offer an explanation. Moreover, occasionally altitude and atmospheric overburden may seem to be in minor disparity. In some cases this may be due to seasonal changes of the barometric pressure. However, in some cases when data are being evaluated some authors take intentionally a somewhat larger overburden than would correspond to the vertical depth to account for the finite zenith-angular bin width and average zenith angle ($\theta > 0^\circ$) within the “vertical” angular bin. Whenever given I have listed the published site data that had been used in the particular case.

Comments on Nomenclature: There is sometimes some confusion in the literature when authors discuss the *shower size* because of inaccurate terminology, which may be a problem for students. Some authors use for the shower size the symbol $N_e$, which implies the *electron size*, but mean in fact the *total shower size* $N$, i.e., the total number of charged particles, $N_{ch}$, in a shower as it is deduced from common particle density measurements that include particles produced by interactions of neutrals (neutrons) and gamma rays (transition effects) in the detectors. In the cases where it is evident that the *all-particle shower size* is meant, I use the symbol $N$ to avoid ambiguities.

On the other hand, in some experiments and in some work the authors clearly deal with electrons only, or chiefly electrons, and mean the actual *electron size* of a shower. In this case I have used the symbol $N_e$ as is appropriate. It is evident that to isolate the electrons from the rest of the particles in a shower is not a trivial matter and a clear distinction is made only in a few experiments. As far as possible I have tried to call the readers attention to the problem whenever it surfaces. For the *muon size* the definition is unambiguous and I have used the symbol $N_\mu$.

Confusing terminology is also frequently encountered in papers that deal with the attenuation of the shower rate or shower frequency and the absorption of the shower particles. Likewise there is no standard for the symbols representing the quantities.

Throughout the book I call the variation of the integral rate of showers of size $\geq N$ with zenith angle $\theta$ (due to the change of atmospheric slant depth) at fixed altitude of observation, $h$, the *shower rate* or *shower frequency attenuation*, and the corresponding attenuation length in the atmosphere the *shower rate attenuation length*, $\Lambda_{\text{att}}$. Analogously I call the variation of the shower size $N$ of given rate (fixed primary energy) with atmospheric depth, $X$, the *shower particle absorption*, and the corresponding absorption length in the atmosphere the *shower particle absorption length*, $\lambda_{\text{abs}}$.

In the latter case, when dealing with muons I use for the *muon absorption length* the symbol $\lambda_{\mu,\text{abs}}$ and, likewise, for electrons only and hadrons only the *electron absorption length* $\lambda_{e,\text{abs}}$ and the *hadron absorption length* $\lambda_{h,\text{abs}}$, respectively. These
quantities and their reciprocals, the shower rate attenuation coefficient, $\mu_{\text{att}}$, and the shower particle absorption coefficient, $\mu_{\text{abs}}$, are defined in Chap. 6. A list of symbols is included at the end of the second volume.

**Comments on Hadronic Interaction Models (Event Generators):** I have devoted some pages for summarizing the physics and mathematics of the early phenomenological high energy hadronic interaction models and discuss the modern models that are based on partons, quark-gluon string and Regge theory more superficially, in form of a catalogue of models, offering only a very brief description of each. However, the relevant references, some of which are very extensive papers, are listed.

The reason for discussing the early models in some detail is that the original papers describing them were published in conference proceedings and journals that are not readily available, yet the models are still of some interest to many. On the other hand, the number of modern low and high energy interaction models (event generators) has grown very rapidly in recent years and they are subject to fast evolution. A detailed description would be quickly obsolete. For this reason I do not discuss them in detail.

**References:** The frequently used abbreviation PICRC stands for Proceedings of the International Cosmic Ray Conference and is used there where the proceedings are not part of a regular scientific journal or series.

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Peter K.F. Grieder
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Extensive Air Showers
Cover

Left: Partial map of the layout of the giant Auger air shower array, covering about 3,000 km², with the four Fly’s Eye type air fluorescence detectors indicated. The detector combination which is located near Malargüe, in Argentina is known under the name Auger Observatory. Its aim is to study the ultrahigh energy (UHE) component of the primary cosmic radiation beyond $10^{17}$ eV, the spectral ankle region around about $5 \cdot 10^{18}$ eV where the extragalactic cosmic ray component is believed to become dominant, to establish the existence of the Greisen-Zatsepin-Kuzmin (GZK) spectral cutoff expected at $\sim 10^{19}$ eV, and to search for correlations between UHE cosmic ray events and astrophysical objects in an attempt to identify objects as sources of UHE cosmic rays (Courtesy of Forschungszentrum Karlsruhe, Germany).

Right: The spiral galaxy NGC 5236 (other catalogue designations are Messier 83 or Southern Pinwheel galaxy) is located in the southern constellation Hydra. It is at a distance of approximately 15 million light years ($\sim 4.6$ Mpc) from our location. Its size is about half of the Milky Way (Courtesy of ESO). I have chosen this picture as a symbolic representative of an extragalactic research object, reflecting the aims of the Auger project to study the extragalactic component of the cosmic radiation, and to find its sources.
To
Estelle
and our
Family
This book grew out of a personal need to carry out my work more efficiently. It was in the 60s when I began to develop the first highly structured air shower simulation program and was carrying out extensive air shower simulations on an almost industrial basis. The primary aim at that time was to study the systematics of hadronic interactions at the highest energies in conjunction with experimental air shower and accelerator data. This goal remains to date but today the determination of the primary mass, its energy dependence and questions related to the origin, acceleration and propagation of the most energetic cosmic rays are in the foreground.

The results obtained with the ever growing shower model that eventually grew into the program system named ASICO (Air shower SImulation and COrelation), which later on became CORSIKA, were so manifold and rich, and covered essentially the full scope of air shower observables that it became necessary to build a library of experimental data for comparison and efficient analysis work; this was the beginning of this book. As the library grew it became evident that it could be of interest to a broader community, active in air shower research. A natural consequence was to add theoretical and tutorial sections to the various chapters, and to expand the book to a comprehensive reference manual for researchers that can also be used as a text book for the advanced student.

The data presented in these two volumes are not an all-inclusive collection. In view of the very large number of experiments that were carried out by so many research groups throughout the years it became unavoidable to take a selection for the presentation here, to compile the data and summarize results. Emphasis was therefore given to the historically as well as the contemporarily scientifically relevant information and data. The fast evolving field of ground based high energy gamma ray astronomy, which employs air shower detection techniques (air Cherenkov as well as particle detection), is only touched on the side, mostly in connection with wide-angle large aperture atmospheric Cherenkov detector arrays. Today, the field of gamma ray astronomy is essentially a separate discipline of its own, yet it remains closely related to cosmic ray and air shower research.
Readme

Organization of the Book: Extensive air showers consist of a superposition of extremely complex processes that involve different fundamental interactions and many aspects of particle physics, cosmic ray physics and astrophysics. Most observables are functions of many variables and parameters and all observables are more or less coupled with each other. This complexity makes it difficult to break up the vast contents of this book into self contained chapters that can be studied separately and in an easily digestible form. I have carefully reflected on how to structure the presentation of the contents of this book and I fully realize that subject oriented sectioning can be done in different ways. A clear structure is of basic importance for the reader and student. No matter how the structuring is carried out, a consequence of the complexity of the subject is that much cross referencing between the chapters is required to link the topics properly. Moreover, an extensive subject index is needed to navigate successfully through the volumes. Both of these requirements are fulfilled and I hope that the reader will be satisfied with the presentation and contents.

The book is divided into two parts that are in two separate volumes. Part I deals mainly with the basic theoretical framework of the processes that determine an air shower. Included are, after the general introduction chapters that describe the shower detection techniques and the basic shower reconstruction procedure using directly accessible shower parameters, followed by a summary of the relevant hadronic, electromagnetic and weak interactions and the cascade formation processes. Subsequently a detailed discussion of the longitudinal, lateral and temporal shower development, and an outline of the complexity and interrelationship of the indirectly observable process and parameters follows. Part I ends with a summary of ways and means to extract information from air shower observations on the primary radiation and presents a compilation of data of our current knowledge of the high energy portion of the primary spectrum and composition.

Part II contains mainly compilations of data of experimental and theoretical nature as well as predictions from simulations of individual air shower constituents, i.e., spectra and distributions of separate components in showers. Also included are chapters dedicated exclusively to special processes and detection methods. These comprise optical atmospheric Cherenkov and fluorescence phenomena that offer special observational windows and have proven to be successful alternatives to particle measurements because they yield three-dimensional insight into the shower process, and radio emission that may possibly develop into a useful future method of detection. I have also included a brief chapter that deals with correlations of shower observables, one that exposes the technique of air shower simulations, and the inevitable chapter on miscellaneous topics. Part II ends with a compilation of definitions and relations, and several appendices that offer useful information. For the benefit of the reader, extensive cross referencing is used that links different yet related topics for rapid access. The extensive subject index at the back of each volume covers both volumes.
**Overview:** With the exception of Chap. 1 (Introduction, Facts and Phenomenology) each chapter is preceded with a brief *Overview* that summarizes the contents and offers directions where to find related topics that some readers may expect to find in the chapter but are discussed elsewhere.

**Comments on Observation Levels:** It will be noticed that sometimes different atmospheric depths or altitudes are specified for a particular site in different chapters and sections, and for different data sets of the same site. This reflects the actual situation in the literature. Most authors do not offer an explanation. Moreover, occasionally altitude and atmospheric overburden may seem to be in minor disparity. In some cases this may be due to seasonal changes of the barometric pressure. However, in some cases when data are being evaluated some authors take intentionally a somewhat larger overburden than would correspond to the vertical depth to account for the finite zenith-angular bin width and average zenith angle (θ > 0°) within the “vertical” angular bin. Whenever given I have listed the published site data that had been used in the particular case.

**Comments on Nomenclature:** There is sometimes some confusion in the literature when authors discuss the *shower size* because of inaccurate terminology, which may be a problem for students. Some authors use for the shower size the symbol $N_e$, which implies the *electron size*, but mean in fact the *total shower size* $N$, i.e., the total number of charged particles, $N_{ch}$, in a shower as it is deduced from common particle density measurements that include particles produced by interactions of neutrals (neutrons) and gamma rays (transition effects) in the detectors. In the cases where it is evident that the *all-particle shower size* is meant, I use the symbol $N$ to avoid ambiguities.

On the other hand, in some experiments and in some work the authors clearly deal with electrons only, or chiefly electrons, and mean the actual *electron size* of a shower. In this case I have used the symbol $N_e$ as is appropriate. It is evident that to isolate the electrons from the rest of the particles in a shower is not a trivial matter and a clear distinction is made only in a few experiments. As far as possible I have tried to call the readers attention to the problem whenever it surfaces. For the *muon size* the definition is unambiguous and I have used the symbol $N_\mu$.

Confusing terminology is also frequently encountered in papers that deal with the attenuation of the shower rate or shower frequency and the absorption of the shower particles. Likewise there is no standard for the symbols representing the quantities.

Throughout the book I call the variation of the integral rate of showers of size ≥ $N$ with zenith angle $\theta$ (due to the change of atmospheric slant depth) at fixed altitude of observation, $h$, the *shower rate* or *shower frequency attenuation*, and the corresponding attenuation length in the atmosphere the *shower rate attenuation length*, $\Lambda_{\text{att}}$. Analogously I call the variation of the shower size $N$ of given rate (fixed primary energy) with atmospheric depth, $X$, the *shower particle absorption*, and the corresponding absorption length in the atmosphere the *shower particle absorption length*, $\lambda_{\text{abs}}$.

In the latter case, when dealing with muons I use for the *muon absorption length* the symbol $\lambda_{\mu,\text{abs}}$ and, likewise, for electrons only and hadrons only the *electron absorption length* $\lambda_{e,\text{abs}}$ and the *hadron absorption length* $\lambda_{h,\text{abs}}$, respectively. These
quantities and their reciprocals, the shower rate attenuation coefficient, $\mu_{\text{att}}$, and the shower particle absorption coefficient, $\mu_{\text{abs}}$, are defined in Chap. 6. A list of symbols is included at the end of the second volume.

**Comments on Hadronic Interaction Models (Event Generators):** I have devoted some pages for summarizing the physics and mathematics of the early phenomenological high energy hadronic interaction models and discuss the modern models that are based on partons, quark-gluon string and Regge theory more superficially, in form of a catalogue of models, offering only a very brief description of each. However, the relevant references, some of which are very extensive papers, are listed.

The reason for discussing the early models in some detail is that the original papers describing them were published in conference proceedings and journals that are not readily available, yet the models are still of some interest to many. On the other hand, the number of modern low and high energy interaction models (event generators) has grown very rapidly in recent years and they are subject to fast evolution. A detailed description would be quickly obsolete. For this reason I do not discuss them in detail.

**References:** The frequently used abbreviation PICRC stands for *Proceedings of the International Cosmic Ray Conference* and is used there where the proceedings are not part of a regular scientific journal or series.

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