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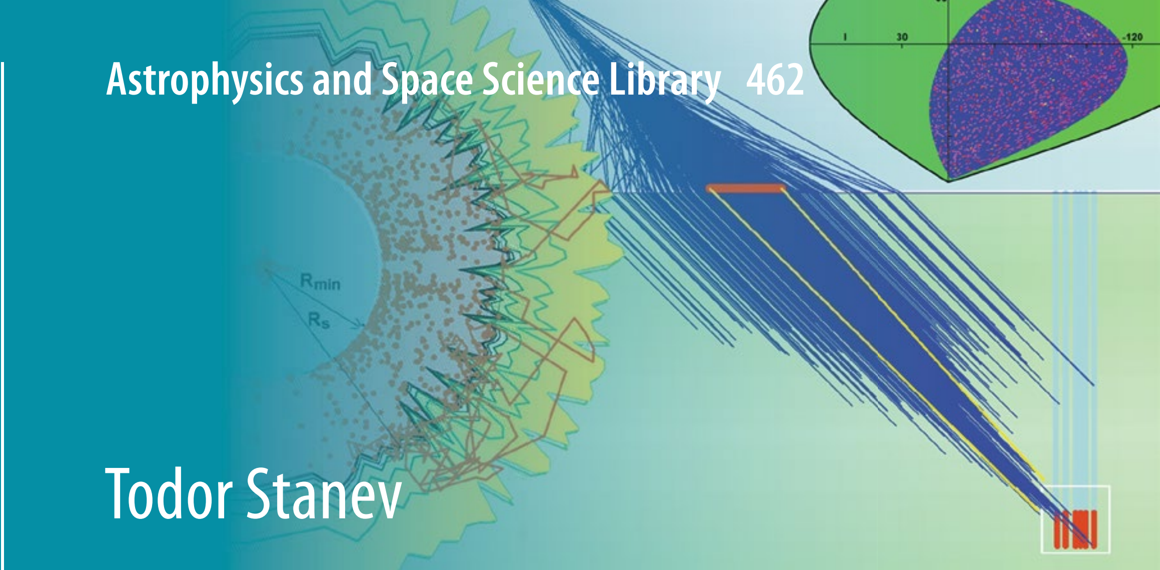

Todor Stanev

High Energy Cosmic Rays

Third Edition

Springer

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Cover illustration: A collage of three images drawn by the author. Right – schematic view of a star showing the different layers through which solar particles travel. Top center – the field of view of a particle detector experiment on the southern hemisphere that can see only a few degrees away from the vertical direction. Left – the components of an extensive air shower that penetrate deep underground to a small detector.

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To my family and friends

Preface to the Third Edition

During the 10 years since the publication of the second edition of the book, research in the fields of gamma-ray and neutrino astronomy advanced a lot. This is especially true for neutrino astronomy, where the IceCube experiment at the South Pole became a research base. I have attempted to describe these developments for the third edition of the book. Very soon we will also have huge detectors of ultra-high-energy cosmic rays in both hemispheres.

While working on the book and other issues, I had the help of my colleague and friend Serap Tilav for which I am grateful.

Newark, DE, USA
September 2020

Todor Stanev

Preface to the Second Edition

The physics of cosmic rays has been a very active field in the years since the first edition of this book was published. There were many new experimental results including the newly measured high-energy spectra of primary electrons and positrons, and the spectrum and chemical composition of the ultra-high-energy cosmic rays. There was an explosion of new results in gamma-ray astronomy, both in the GeV and the TeV energy ranges. Neutrino astronomy is developing very fast, and although we still have not detected astrophysical sources of high-energy neutrinos, it has become an observational science. The second edition of this book became necessary to include these new results and developments.

The author is grateful to the colleagues and friends who read the first edition very carefully and reported all typos and inexact expressions they found. Most of this work was done by P. L. Biermann, R. Engel, and H. Vankov.

I thank my colleagues from the Laboratoire de Physique Nucleaire et de Hautes Energies (LPNHE) at the University of Paris VI, and specifically Antoine Letessier-Selvon, for their hospitality in the fall of 2009 when work on the second edition was completed.

Newark, DE, USA Todor Stanev
November 2009

Preface to the First Edition

This book discusses the processes and the astrophysical environment that lead to the acceleration of cosmic rays and govern their propagation through the galaxy to the solar system, and through the solar system to Earth. Most of these processes are also used in different methods of cosmic ray detection. The book also gives many samples of cosmic ray data and their physical interpretation.

I am grateful to many colleagues for their contribution to my understanding of cosmic rays, starting from my early days in cosmic rays physics. Among them are B. Betev, M. Block, A. Franceschini, J. G. Learned, M. M. Shapiro, A. A. Watson and G. Yodh, with whom I have worked on some specific topics.

Special acknowledgements are due to my frequent collaborators who enhance my knowledge of the subject. This long list includes most of all Tom Gaisser and also Jaime Alvarez-Muñiz, Venya Berezinsky, Peter Biermann, Ralph Engel, Francis Halzen, Paolo Lipari, Raymond Protheroe, Jörg Rachen, David Seckel, Hristofor Vankov and Enrique Zas.

I thank my colleagues from the Laboratory for Particle Physics and Cosmology, Collége de France, and its director Prof. Marcel Froissart for their hospitality in 2001/2002 when the main body of the book was planned and the writing began.

It would be impossible to complete this book without the support and encouragement of my extended family.

Newark, DE, USA
December 2003

Todor Stanev

Contents

Chapter 1
Overview

Cosmic rays are often defined as charged particles that reach the Earth from interstellar space. This definition describes correctly the majority of the cosmic ray particles which do consist of fully charged nuclei. At GeV energy the flux of hydrogen and helium nuclei dominate all other species. The chemical composition of cosmic rays extends to very high masses and we believe that cosmic rays include in various degrees all stable nuclei. In addition there is a steady flux of electrons which are also included in the above definition. Other, although not very common, components represent anti-matter—these are the antiprotons and positively charged electrons—positrons.

Neutral particles are obviously not included as a cosmic ray component. So are all kinds of particles that are not of interstellar origin. We will, however, deviate from the definition and deal with all types of neutral particles and occasionally with particles generated by the Sun, such as the solar neutrinos that provided the proof of the nuclear processes that power the Sun.

The way cosmic rays are approached in this book is similar to the list of topics discussed at the International Cosmic Ray Conference—a big scientific forum that meets bi-annually. At the last ten meetings the contributions to the meeting were divided into three sections: cosmic ray origin and Galactic phenomena, high energy phenomena and solar and heliospheric physics. We will discuss mostly the first two aspects of the field and touch the third one only when it also applies to the propagation of galactic cosmic rays in the heliosphere.

The third edition of the book keeps the general structure of the second edition and discusses more recent results published during the last 10 years.

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1.1 Where Does the Cosmic Ray Field Belong?

This is a very difficult question that I have trouble answering when inquisitive co-travelers ask it of me in the airport. From the division of topics at the bi-annual meetings it is obvious that cosmic ray physics is a cross-disciplinary area where astrophysicists, high energy particle physicists and plasma physicists work together.

The field has been like that from the very beginning—the discovery of the cosmic ray radiation more than 100 years ago. At this time the research that led to the discovery was a cross between physics, material science and environmental studies. After the discovery of radioactivity it was noticed that the air is being ionized at a relatively high rate. The measurements showed that 10–20 ions were generated in a cubic centimeter of air every second. Was that inherent to the material or a product of the natural radioactivity of the Earth—this was the main question. Three types of radioactive rays were known at that time: α-rays (ionized He nuclei), β-rays (electrons) and γ-rays. Since the first two were very easy to shield from, γ-rays were suspected to be the ionizing agent.

The ionization was measured at different heights in towers, including the Eiffel tower, in attempts to figure out what the penetration power of these γ-rays is. The breakthrough occurred just before the First World War when Victor Hess in Austria and Kohlhörster in Germany decided to make measurements from balloons. In 1912 Hess flew in a balloon to altitudes of 5 km and discovered that, instead of decreasing, the ionization of the air strongly increases with altitude. The only explanation of his measurement, he believed, was that 'a radiation of very high penetrating power enters the atmosphere from above'. This marked the discovery of cosmic rays for which Hess received the Nobel prize in 1936.

Kohlhörster contributed a lot to these first measurements with his flights that reached altitude of 9 km. After the war the altitude dependence of the ionization became the topic of many measurements at different locations and altitudes. Maybe the biggest contribution was that of Millikan, which is ironic since he aimed at disproving the results of Hess and Kohlhörster. Millikan improved the detection technology and started measurements of the ionization with instruments that were lowered in mountain lakes at different depths. Since the total thickness of the atmosphere corresponds to only about 10 m of water, Millikan believed that his measurements in water will determine better the absorption length of the cosmic radiation.

Figure 1.1 compares the results of Kohlhörster with two of the lake experiments of Millikan. Millikan first used 'cosmic rays' to describe the radiation and thus created the current name of the field. His idea was to reveal the origin of cosmic rays through the energy of the cosmic rays, which he believed are γ-rays from the nucleosynthesis of the common elements like helium and oxygen, ranging in energy from 30 to 250 MeV.

The experimental results did not help him, because (as it is obvious from Fig. 1.1) cosmic rays have different absorption lengths in the atmosphere and in water. This is a result that we easily understand now, when we know that these are measurements of two different components of the atmospheric cosmic

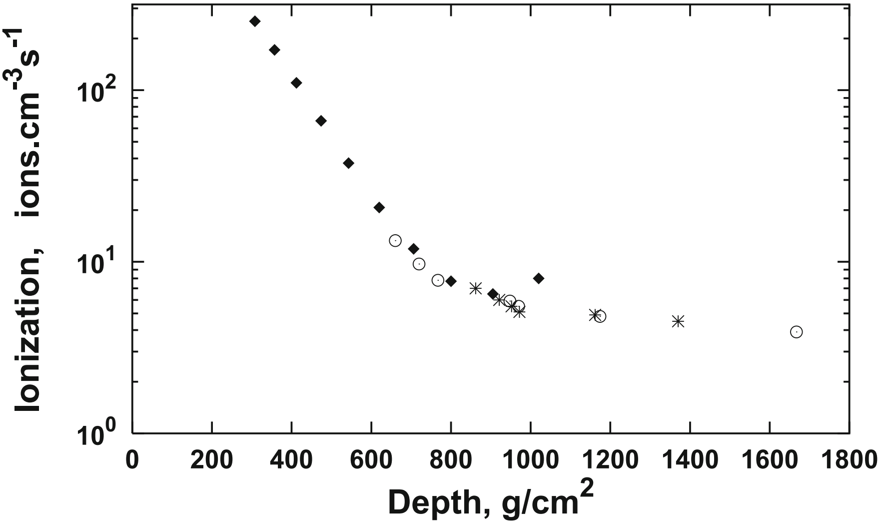

Fig. 1.1 The ionization as a function of the depth in the atmosphere. The diamonds are from the flight of Kohlhörster and the circles and asterisks are from the under-water measurements of Millikan

ray showers—the electromagnetic component in air and the penetrating muon component under water.

During the following 20–30 years cosmic ray research concentrated on the high energy physics properties of cosmic rays. There were no other sources of high energy particles and most of the discoveries of new particles before 1950 were made in measurements of the cosmic ray interactions.

Other related progress was the development of the quantum electrodynamics (QED) and the electromagnetic cascade theory that followed the discovery of cosmic ray induced showers in 1929 by Skobelzyn. These showers were first interpreted as a result of Compton scattering by the cosmic γ-rays. The theory of the electromagnetic interactions was soon developed and the theory of electromagnetic showers was fully developed by 1940.

The explosion of new discoveries became possible because of several new ways for direct detection of shower particles. Skobelzyn observed directly shower tracks in a cloud chamber. The cosmic ray particles ionized the material in the chamber and made their tracks visible. The amount of ionization could be measured by the thickness of the track. A similar way to see the tracks and to measure more precisely the amount of ionization was to use nuclear emulsion stacks. Layers of photo emulsion were stacked together and exposed to cosmic rays. The emulsion was later developed to see and match the tracks. It is a complicated and time-consuming method, but has unmatched accuracy and its principle is still used today.

In addition to viewing tracks, cosmic ray physicists learned how to count charged particles. The first successful device was the Geiger–Müller counter that gave a pulse after a charged particle passed through it. These counters make the particle detection much easier. They do not explicitly recognize the particle energy, but they could be shielded with amounts of matter that define the threshold energy of the particles to penetrate through the shielding.

The development of the experimental techniques made possible the important progress in the discovery of the nature of cosmic rays. The initially used electrometers were replaced with counters of charged particles. When two counters were positioned one above the other both of them measured particles simultaneously, i.e. the measured particle had enough energy to penetrate through both counters. Even higher penetrating power was proved when several centimeters of lead or gold were placed between them. This proved that some of the cosmic ray particles are very different from γ-rays.

In a different type of experiments counters were put on the same level but at different distances from each other. The coincidences between the two counters demonstrated that some of the cosmic rays come to the surface of the Earth in groups—as atmospheric showers. The measurements of the rate of coincidences as a function of the distance between the counters and the application of the shower theory led to the conclusion that the primary particles that initiated the atmospheric showers have energy as high as 10^6 GeV.

In several years this was confirmed by nuclear emulsion experiments that were exposed to primary cosmic rays in high altitude balloon flights. Tracks of protons and heavier nuclei were discovered in the emulsion stacks which finally proved the true nature of cosmic rays. For a while cosmic ray experiments became the experimental side of nuclear physics.

Another track of the cosmic ray research in the same period was a study of the cosmic ray interactions with the geomagnetic field. Once the scientists knew that cosmic rays were positively charged nuclei they figured out that the cosmic ray flux would depend on the strength of the magnetic field at the location of the experiment. This was confirmed, not without some controversy, in many scientific expeditions during which cosmic rays were measured at different geomagnetic latitudes.

The same type of experiments also discovered the 'east–west' effect—because of the direction of the geomagnetic field more primary cosmic rays come from the west than from the east. Positive particles coming from the west bend downwards—towards the atmosphere and the surface of the Earth, while the ones coming from the east bend away from the Earth. The effect is stronger and thus easier to measure at high geomagnetic latitude.

With the fast progress of the particle accelerators in the 1950s and 1960s cosmic rays lost their attraction for the majority of high energy physicists. Accelerators provided intense beams of known particle type and energy. A measurement that would last many years in cosmic rays could now be completed in hours. Experimental arrangements were much more sophisticated. They could be constructed to surround the known position of the particle interaction with the target. The results were precise because of the known primary energy and the better detection technique. There was only a relatively small group of physicists who were concerned with interactions well above the energy achievable by particle accelerators. The energy range kept increasing—as soon as a new accelerator was built the cosmic ray physicists had to jump to higher energy.

As squeezed as the field was, the results from the accelerator laboratories were God's gift for these remaining cosmic ray scientists. The characteristics of hadronic interactions became much better known and the analysis of the cosmic ray data improved significantly. The reputation of the field, however, decreased and this resulted in mass exodus of cosmic ray scientists to accelerator labs. At the same time there was a significant progress of the field in different directions.

The experimental study of the solar system led to the existence of what we now call 'space physics'. The magnetic fields in the heliosphere and the properties of the solar wind were studied in more and more detail. The behavior of the cosmic rays in the heliosphere became a major research topic. Results from measurements of the total cosmic ray intensity on the surface of the Earth at different geomagnetic latitudes (e.g. with different energy threshold) were compared to intensities measured by satellites and space missions and were related to the epoch of the solar cycle and the level of solar activity.

The possibility of studying directly primary cosmic rays with experiments mounted on balloons and satellites also led to a great precision of the knowledge of the chemical and isotopic composition of cosmic rays. The experimental progress inspired similar progress in the investigations of the formation of the measured chemical composition and its relation to the composition at the cosmic ray sources. The nuclear reaction cross-sections were measured in the laboratory by cosmic ray physicists and were applied to the cosmic ray interactions in their propagation in interstellar space. The detection of known unstable isotopes and the comparison of their fluxes allowed independent estimates of the cosmic ray containment time in the Galaxy.

At the same time there was rapid development in the theory of cosmic ray acceleration. Several models appeared almost simultaneously in the late 1970s that described the cosmic acceleration at astrophysical shocks. The combination of the results of these new developments led to the creation of what I call the *standard model of cosmic rays*.

The positive evolution in the development of the *standard model* still continues and the study of the cosmic ray propagation in the Galaxy and the heliosphere are now much more sophisticated and conclusive. A new development started about 40 years ago which eventually formulated the current status of the field. The early bird was the solar neutrino experiment set up by Ray Davis in the Homestake mine. Davis attempted to measure the neutrinos coming from the nuclear reactions at the Sun. By the early 1970s the results of this experiment attracted interest because of the missing solar neutrinos. At about the same time the extensive progress in particle theory developed scenarios in which the proton was not a stable particle and had a lifetime of the order of 10^{30} years, i.e. 20 orders of magnitude longer than the age of the Universe.

Huge experiments were built in the early 1980s to measure proton decay. They contained more than 10^{33} protons and were located deep underground to shield the reaction, which releases energy equal to one proton mass, from penetrating cosmic rays. Only limits on the proton lifetime exist now, but these experiments hinted that the muon neutrinos generated in the atmosphere by cosmic rays are also missing and extended the already existing hypothesis of neutrino oscillations.

As one will see in this book deep underground experiments can measure many different effects, only some of which are related to neutrino oscillations. The exciting set of topics started attracting many high energy accelerator physicists back to the cosmic ray field—although generally from the next age generation. Now deep underground physics is a fashionable field, with plans for new giant experiments that only define the topics of the study and do not separate the physicists into accelerator or cosmic ray ones.

In the early 1980s, perhaps inspired by the advent of X-ray and γ-ray astronomy, cosmic ray physicists started looking at the exact direction from which high energy cosmic rays arrive at the Earth. The first suspicion that some very high energy particles come from the binary system Cygnus X-3 may not be correct, but the ambition for the development of cosmic ray astronomy that it created had a positive role for the development of the field. It coincided with the first measurements of TeV γ-rays, which on its own led to the current construction and operation of the third generation of telescopes.

During the last 30 years many particle physicists became curious about the origin and nature of the highest energy cosmic rays. The current generation accelerator, the Large Hadron Collider(LHC), studies particle interactions at equivalent laboratory energy of about 4×10^8 GeV, while particles of energy exceeding 10^{11} GeV have been detected in cosmic rays. How can Nature achieve higher energy than a perfectly engineered and fabricated machine? What are the objects that are capable of squeezing the energy of the fastest tennis ball into a volume less than 10^{-38} cm^3? Huge ground experiments are built to observe these highest energy events and satellite experiments to detect them are now being considered.

Particles of such high energy have interactions in extragalactic space and may be deflected by magnetic fields, while high energy neutrinos could reach us from the edge of the Universe and point at their sources. Although such neutrinos are rare, their detection creates a new type of astronomy that does not observe electromagnetic waves. High energy neutrino astronomy underwent very rapid development during the last 20 years. Now two experiments, one in each hemisphere, shielded by kilometers of water and ice observe the whole sky for sources of high energy neutrinos. Their results are complementary to those at all photon frequencies and to the detection of ultra high energy cosmic rays. There has never been a better chance to finally solve the problem of the origin of all cosmic rays.

I did not intentionally leave the reader wondering where the field of cosmic ray physics belong in the classification of different fields. It certainly contains, contributes to, and benefits from the research of many fields of physics and astrophysics. A better definition than an outline of its history and its ever-changing priorities is hardly possible.

1.2 Is Progress in the Cosmic Ray Field Slow?

It certainly looks like that. Cosmic rays were discovered more than 100 years ago and we are still asking questions about their exact origin and even, at ultra high energy, about their nature. One can understand the degree of progress only after a careful examination of the achievements in the field and the current knowledge of cosmic rays.

We shall start with the energy range that cosmic rays cover. Figure 1.2 shows the energy spectrum of cosmic rays above 100 GeV per nucleus. This includes all charged nuclei. We only show this restricted energy range, because at lower energy the experiments are exact, but the instruments cannot cover the whole mass range. In that region the usual way of presenting the nuclei of different mass is in kinetic energy E_k per nucleon, and the conversion to energy per nucleus requires fitting and respectively introduces errors. The smooth cosmic ray spectrum becomes a wavy line.

At 100 GeV the difference betweenE_k and total energy per nucleon is the proton mass $m_p = 0.938\,\mathrm{GeV}$ and the spectra measured in both units almost coincide. At lower energy they do not. In addition to the ten orders of magnitude shown in Fig. 1.2 cosmic rays include five more decades in kinetic energy.

The cosmic ray energy spectrum in Fig. 1.2 is an almost featureless power law spectrum with two transition regions where the slope of the spectrum changes. What is important for our discussion here is that the number of particles above 100 GeV is higher than that above 10^{11} GeV by sixteen orders of magnitude. The units of integral flux at three energies quote the approximate number of particles above that energy that hit the atmosphere. Six particles per square kilometer per minute is relevant for energy of about 10^7 GeV. A typical instrument of area 1 m^2 will have to wait for 2 years to detect a single particle above that energy. Even the measurements of the air showers initiated by these particles in the atmosphere last for many years. The low flux of cosmic rays at very high energy is one of the reasons for the slow and difficult progress in their understanding.

Another reason is the necessity for particle and nuclear physics input in the analysis of indirect cosmic ray experiments, such as air showers. The first accelerator that studied hadronic interactions at energies applicable to Fig. 1.2, ISR, started working in 1971, more than 30 years after the existence of cosmic ray particles of that energy was shown by Pierre Auger. And ISR studied proton–proton not nucleus–nucleus collisions. The adequate analysis of the events and the reconstruction of the primary particle characteristics at high energy was, and still remains, difficult and model dependent.

The argument, however, works both ways. The current, and possibly last, accelerator at record energy, the Large Hadron Collider, reaches the equivalent laboratory energy of approximately 4×10^8 GeV. The only way to measure the evolution of the hadronic interactions at higher energy and test their understanding and the theoretical models is through studies of more energetic cosmic ray interactions.

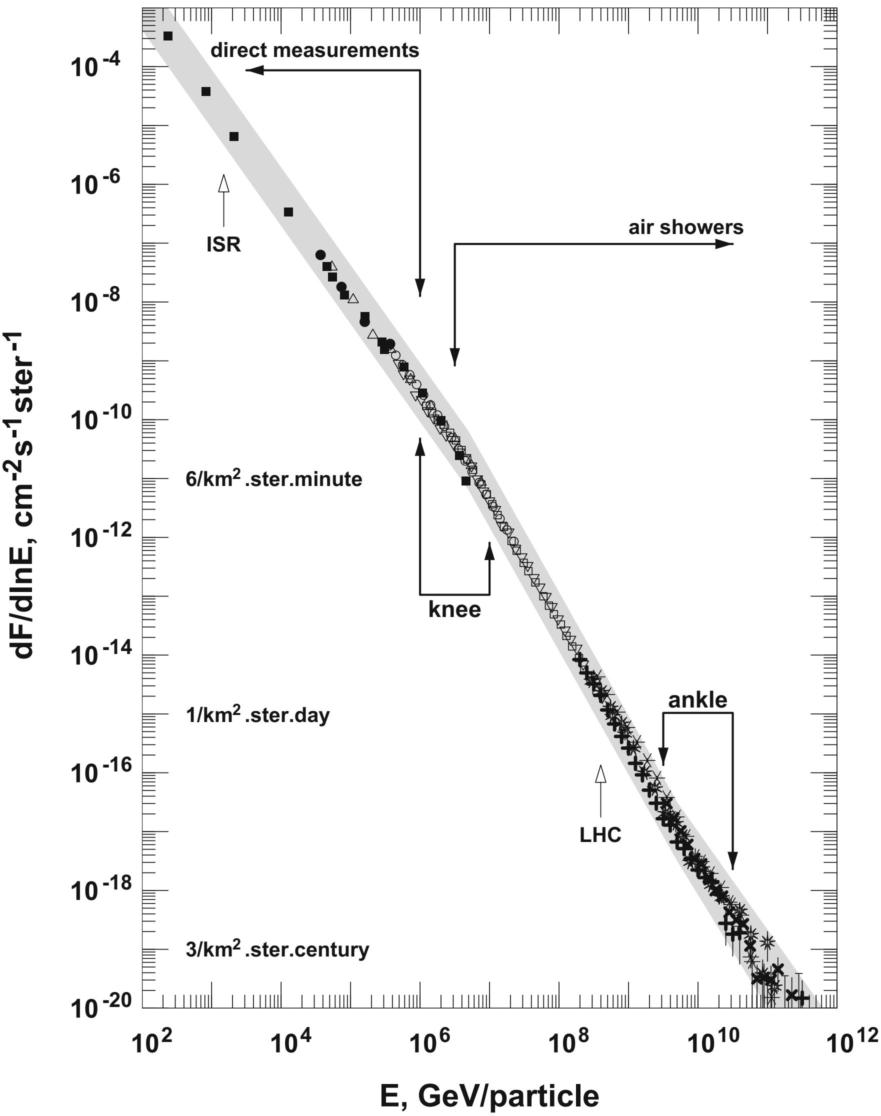

Fig. 1.2 Energy spectrum of all cosmic ray nuclei above 100 GeV

If we come back to Fig. 1.2, we can roughly identify the two positions at which the spectral index changes and the three energy ranges they define. The region between 10^6 and 10^7 GeV where the cosmic ray spectrum becomes steeper is called the 'knee'. Below the 'knee' the number of particles decreases by a factor of 50 when the threshold energy is increased by ten. Above the 'knee' this factor is about 100. At higher energy the spectrum becomes again flatter at the 'ankle'. We believe that cosmic rays below the ‘knee’ are accelerated at supernova remnants, that particles of energy between the ‘knee’ and the ‘ankle’ come from some other galactic sources (possibly nonstandard supernova remnants) and that the highest energy particles are of extragalactic origin.

To develop a solid theory of the origin of cosmic rays in the whole energy range one needs detailed information about all possible sources and their environments. We have to know the structure and the strength of the magnetic fields and their extension. In spite of the huge progress in astrophysics during the past 30 years such information is only available for a small number of objects. The conditions in interstellar and extragalactic space are even less known.

This argument can also be turned around. The understanding of the details of cosmic ray diffusion in the Galaxy, and respectively the chemical composition of cosmic rays at their sources will lead to additional progress in astrophysics. The solution of these problems is done through trial and error—build a model and test it, understand why it does not work and then build a better model. This is a slow process.

The process of research contains periods of frustration and dissatisfaction, but I would not agree that the progress in cosmic ray physics is slower than in many other fields. The field involves relatively few scientists and its progress is balanced with the progress in the other disciplines that it requires input from and that use its results.

1.3 Main Topics for Future Research

All predictions for the future of a scientific field are very uncertain. I will take the risk and attempt to outline the regions where the need for quick progress is urgent and the chances for such progress are good.

The first region is probably the measurement of the cosmic ray chemical composition in the region of the ‘knee’ at about 3×10^{15} eV. At GeV energy hydrogen and helium nuclei dominate the cosmic ray spectrum but there are indications that heavier nuclei have energy spectra flatter than hydrogen. The tendency is that the average mass of the cosmic ray nuclei increases with energy. This is a widely accepted fact although the details of the energy dependence vary from analysis to analysis.

If, as we currently believe, the ‘knee’ of the cosmic ray spectrum marks the limiting energy for a class of cosmic ray accelerators, the composition should become heavier when that limit is approached. The reason is that the limiting high energy for a nucleus is proportional to its charge. The proton spectrum from an accelerator will cut off at total energy 26 times lower than the cutoff of iron. If a new type of accelerator takes over at higher energy one should expect that, at least at the beginning, hydrogen and helium nuclei will again dominate and the average mass will decrease.

As we explore the cosmic ray energy spectrum we will find severeal energy values where the shape of the energy spectrum changes. At the *knee* the spectrum becomes steeper. There are places where the spectrum becomes somewhat flatter. It is still difficult to understand why such changes happen. All we can do is to try to describe correctly the changes of the energy spectrum and the corresponding changes of the cosmic ray composition if such changes occur. Hopefully in the near future these experimental data will lead to a solution.

The exact solution of this problem cannot be achieved in theoretical investigations. It needs better experimental data. These consist of two different types. Sophisticated modern detectors fly at the International Space Station and measure directly the cosmic ray chemical composition up to 10^6 GeV. Such data provide an overlap with measurements of air showers on the ground. This overlap can be used to improve the analysis of the air shower experiments, which are the only experiments that can reach the highest cosmic ray energies.

Considerable progress has already been made in the use of standard hadronic interaction models and shower simulation codes. Because of this we can now judge objectively the differences between the various experimental approaches and results.

A second topic of high current interest is the end of the cosmic ray spectrum. This is the region marked with 3 particles per square kilometer per steradian per century in Fig. 1.2. One needs experiments with an effective area of thousands of square kilometers to collect reasonably good statistics. Such experiments are now operational. They have increased the world statistics by a large factor during their first years of operation. It is very important that these experiments do not only measure the energy, but also investigate the type of the primary cosmic ray particles. This will give us an important clue for the processes that create the highest energy particles in Nature.

There are also ambitious projects for the construction of space-based air shower experiments that will have effective areas in millions of square kilometers. Some of these projects may be realized on a timescale of 10–20 years.

The third topic is the creation of a new type of astronomy—the high energy neutrino astronomy. Optical astronomy is possible only when the astrophysical objects are not obscured by large amounts of matter. Higher energy photons penetrate matter more easily, but at an energy above 1000 GeV start interacting with the isotropic optical and infrared background and, at still higher energy, with the microwave background. Only neutrinos can penetrate the Universe without interactions at energies higher than 10^5 GeV.

There is also a different reason for the development of neutrino astronomy. Everything we touch consists of protons, neutrons and electrons. The number of protons in cosmic rays is about 100 times higher than the number of electrons. Astrophysics, however, considers almost exclusively electromagnetic processes, and does not account for the very likely presence of nucleons and hadronic interactions. Photons of all energies will be created in both electromagnetic and hadronic processes. Neutrinos belong exclusively to hadronic and nuclear interactions. Detection of high energy neutrinos of astrophysical origin will reveal the importance of hadronic interactions in astrophysical objects.

The construction of the first high energy neutrino telescope was finished 10 years ago. The observational technique was proved and now a cubic kilometers detector is working at the South Pole. Another large neutrino telescope is working in the Mediterranean. We have realized a new observational technique that will help us understand the Universe better.

1.4 How this Book is Organized

The idea for this book originated more than 20 years ago. I was asked if I was interested in writing a book on cosmic rays. My first reaction was that there were many good books on this subject and I would hardly be able to write a better one.

I should list here the books I admire and which have contributed much to what I know about cosmic rays. The first one I want to acknowledge is the book of Rossi [1]. Rossi presents the 1952 knowledge of cosmic rays and particle physics in a very clear and exact way. The book contains a still very useful description of electromagnetic cascade processes. The book of Ginzburg and Syrovatskii [2] set the stage for the current standard theory of cosmic rays. The book of Hayakawa [3] discusses both the physics of cosmic ray detection and the astrophysics aspects of cosmic ray research. Some parts of the book are now outdated. The book of Hillas [4] contains elegant original derivations of many cosmic ray properties. It also contains reprints (and translations) of 14 important classical cosmic ray articles.

The book of Berezinsky et al. [5] covers all astrophysical aspects of cosmic rays in a consistent manner. The book of Gaisser [6] has become very popular because it derives the basic equations that govern the development of cosmic ray cascades and gives the reader the instruments to calculate the fluxes of secondary particles. The book of Longair [7] uses cosmic ray examples to illustrate many processes in high energy astrophysics. Grieder [8] has collected a large amount of cosmic ray data and presents them with a clear brief explanation of the relevant processes. Schlickeiser published [9] a book that contains exact definitions and plasma processes descriptions. And for those who want to learn more about solar energetics and solar neutrinos I recommend the book of Bahcall [10].

Eight years ago K.-H. Kampert and Alan Watson published an excellent article on the history of the studies of cosmic rays [11]. People interested in cosmic ray research would gain a lot from this article.

This book is divided in two parts. Part I describes the *standard model of cosmic rays* and gives some of the data that helped its construction. It starts with a short introduction to the interactions that are important for understanding the processes that are included in the model. The process description is limited to low and moderate energies and does not include their high energy extensions.

Chapter 3 starts with some knowledge of the astrophysical processes that precede the cosmic ray acceleration. It briefly describes solar energetics, stellar evolution, supernova explosions and supernova remnants. I also include data on solar and supernova neutrinos—the results of observations that were crucial for the confirmation of the theoretical predictions for stellar evolutions. Some of the subsections are typed in *italic*. They contain more detailed information than the general flow of the subject requires and can be skipped by a reader who has no interest in these topics. Sections in *italics* appear in all chapters of Part I. The second section of Chap. 3 deals with the acceleration of charged particles. The description is not very detailed—it only aims to familiarize the reader with the basic acceleration scenario.

Chapter 4 is dedicated to the passage of the cosmic rays through the Galaxy. It gives some basic information about the conditions in interstellar space, introduces a model of the galactic magnetic field and charged particle propagation in random magnetic fields. The next topic is the change of the chemical composition of the cosmic rays in their diffusion through the Galaxy. Cosmic ray pathlength and escape time are estimated on the basis of their isotopic composition. An additional source of information about the cosmic ray diffusion in the Galaxy, the isotropic flux of GeV γ-rays generated by cosmic rays, is discussed at the end of this chapter.

Chapter 5 is the first of three chapters that describe the experimental data taken at the top of the atmosphere, at the Earth's surface and underground. It starts with a brief description of the different types of detectors and of the changes in cosmic rays that are caused by heliospheric and geomagnetic effects. Then it gives the general picture of the cosmic ray spectrum and composition as measured by satellite and balloon experiments, followed by more detailed data on separate nuclear components. The chapter ends with a discussion of the fluxes of cosmic ray electrons and antiprotons.

Chapter 6 deals with cosmic ray processes in the atmosphere. It starts with the structure of the atmosphere and gives some of the analytic solutions for the atmospheric fluxes of secondary particles. The fluxes of atmospheric muons are then given and compared to Monte Carlo calculations.

Chapter 7 is devoted to the muons and neutrinos that are detected in underground experiments. It discusses high energy muon energy loss and propagation through rock and water and gives the exact formulae for the different energy loss processes. The next topic is the production and detection of atmospheric neutrinos. The section gives the neutrino interaction cross-sections as a function of the neutrino type and energy and discusses experimental results from different methods of atmospheric neutrino detection. The chapter ends with an introduction to neutrino oscillations that covers both atmospheric and solar neutrinos.

The second part of the book describes the contemporary challenges in cosmic ray research. It covers the three topics introduced in Sect. 1.3. Chapter 8 starts with a general discussion of cascades on the basis of the electromagnetic cascade theory. The accuracy of the theoretical approaches is discussed in comparison to Monte Carlo calculations. Attention then is drawn to hadronic showers at high energy. First a simple shower phenomenology is discussed and different detection methods and experimental arrangements are introduced together with the extension of the hadronic interaction models to high energy. The chapter ends with the methods for analysis of air showers and the data for the cosmic ray spectrum and composition at and above the 'knee' of the cosmic ray spectrum.

Chapter 9 discusses the end of the cosmic ray spectrum. It starts with an introduction to the energy loss of the cosmic ray nuclei in propagation in extragalactic space. Individual giant air shower detectors that have been built to explore the end of the cosmic ray spectrum and their results are followed by models for production of ultra high energy cosmic rays. The next topic is ultra high energy cosmic ray astronomy—the arrival directions of these particles are discussed together with the results of proton scattering in galactic and possible extragalactic magnetic fields. The chapter ends with a description of future giant air shower detectors.

The last chapter discusses the topic of high energy neutrino astronomy. High energy γ-ray astronomy results and analyses are used to identify potential sources and signal strengths in galactic and extragalactic sources. Individual sources are described and predictions are given for the high energy neutrino flux. Neutrinos from the propagation of ultra high energy protons are introduced to justify the relation between ultra high energy cosmic rays and high energy neutrinos. The book discusses the possible methods for neutrino detection and projects for different types of neutrino telescopes.

The second part of the book has been fully rewritten for the third edition. It was necessary to do that because of the wealth of new detectors and new results in the air shower measurements and in γ-ray astronomy, where we have so many new γ-ray telescopes. Neutrino astronomy is also developing very quickly and needs a serious update.

The reader should know that almost all the figures in this book have been generated by the author. Two of the figures have been drawn by my colleague and friend Serap Tilav.

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Part I
The Standard Model of Cosmic Rays

Chapter 2
Cosmic Ray Interactions

This book is not a book on high energy physics and particle interactions. We have, however, to give the reader some information on the structure of matter and the interactions between its building blocks, because these are necessary for the understanding of the phenomena of cosmic ray acceleration, propagation in the Universe, and detection.

This chapter gives a simple introduction to our understanding of the structure of matter and of the different interactions that cosmic rays undergo in their propagation from their sources to us. The description of the interactions is brief and biased toward higher energy particles, with an energy of about 1 GeV and higher, which are the main subject of our interest. Three types of interactions are discussed:

- electromagnetic interactions of charged particles, which in are mostly important for the propagation of electrons and photons;
- inelastic hadronic interactions, that are important for the production of secondary particle fluxes;
- nuclear interactions, when heavier nuclei are split into lighter ones, that are mostly important for changes of the chemical and isotopic composition of accelerated cosmic ray nuclei.

We will not discuss the weak interactions in this section. Discussion and formulae for the interactions of neutrinos will be given in Sect. 7.2.1.

2.1 Components and Structure of Matter

The progress in understanding the structure of matter is intimately and naturally linked to the exploration of smaller and smaller dimension. Rutherford's experiments revealed the existence of the atomic nucleus which takes up a very small fraction of the volume of the atom. Nuclei consist of their components, protons (p)

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and neutrons (n). The electrons (e^-) are negatively charged particles that orbit the positively charged nucleus to complete the atom.

With the exceptionally rapid development of the experimental particle physics in the last 50 years the number of such 'elementary' particles became very large. The *Review of Particle Properties* [1], that keeps track of all results in the field, lists more than 100 particles the existence of which is firmly established and whose properties are well known. Most of these particles are not stable. They decay with a very short lifetime. The long-living π^+ decays in 0.026 μs and most other lifetimes are shorter by many orders of magnitude. There are also as many particle 'candidates', the properties of which are not well known and which do not satisfy the conditions for fully established 'elementary' particles.

A few of these particles, such as the electron and electron neutrino (ν_e) are truly elementary, i.e. they are indeed among the building blocks of matter. Both the electron and the neutrino are *leptons*. Others, the *hadrons*, are combinations of smaller blocks, *quarks*, which have never been observed individually, in isolation. Their properties have been derived from the properties of the hadrons they build up because of the conservation of the quantum numbers that these particles carry. A third type of particles is called gauge bosons. These carry the forces between the hadrons and the leptons.

Table 2.1 gives information about the properties of some of the quarks and leptons. Each quark and lepton has its antiparticle. A proton consists of two up quarks and one down quark. Its structure is uud. Consequently it has a baryon number of $1(1/3 + 1/3 + 1/3)$ and charge $+1(2/3 + 2/3 - 1/3)$. All charges are measured in units of the electron charge. A neutron consists of one up quark and two down quarks (udd). It is neutral $(2/3 - 1/3 - 1/3)$ and has a baryon number 1. The antiparticle of the proton, the antiproton consists of $\bar{u}\bar{u}\bar{d}$. It has a charge of -1 and baryon number -1. All baryons are *strongly* interacting particles. Other hadrons, which also interact strongly, are the mesons. Mesons consist of a quark–antiquark combination. The positive pion π^+ is a ($u\bar{d}$) combination and has a charge of 1 $(2/3 - (-1/3))$ and baryon number 0 $(1/3 - 1/3)$.

Quarks have also an additional quantum number specific to them, *color*, which allows the combinations of identical quarks, which otherwise would have been forbidden by Fermi's statistics. The classical example for that is the doubly charged baryon Λ^{++} which consists of three up quarks (uuu) of different colors.

Table 2.1 Basic building blocks of matter

Name	Baryon number	Lepton number	Charge
Quarks:			
Up (u)	1/3	0	2/3
Down (d)	1/3	0	$-1/3$
Leptons:			
Electron (e^-)	0	1	-1
Electron neutrino (ν_e)	0	1	0

Table 2.2 Quarks, leptons, interactions they participate in, and the force carriers

Name	The three families			Interactions	Gauge boson
Quarks	u (up)	c (charm)	t (top)	strong &	g
	d (down)	s (strange)	b (beauty)	EM	γ
Leptons	e (electron)	μ (muon)	τ (tau)	EM &	γ
	ν_e	ν_μ	ν_τ	weak	$W^\pm$, Z

2.1.1 Strong, Electromagnetic and Weak Interactions

The particles shown in Table 2.1 represent only one of the three families of quarks and leptons. Table 2.2 gives the names of all quarks and leptons and the types of their interactions. All charged particles have electromagnetic interactions. Hadrons have also strong interactions and neutral leptons have only weak interactions. These three types of interactions reflect the strength and extension of the corresponding forces. The strong force has a short range of the order of the radius of a proton ($1\text{fm} = 10^{-13}$ cm) and strength α_s of 1. The force is carried by gluons (g). The electromagnetic force is carried by γ-rays and its coupling constant α has strength lower by two orders of magnitude. The weak force is carried by the intermediate vector bosons $W^\pm$ and the neutral Z and has a coupling α_W of the order of $10^{-6}\alpha_s$.

These features are also reflected in the corresponding particle decays. Weak decays, like $\pi^+ \rightarrow \mu^+\nu_\mu$ have lifetimes in excess of 10^{-12} s. Note the conservation of the quantum numbers in the decay. The sum of the lepton numbers of the decay products is 0, as is that of the parent π^+. Electromagnetic decays ($\pi^0 \rightarrow \gamma\gamma$) have lifetimes shorter than 10^{-16} s, while decays guided by the strong force have lifetimes of the order of 10^{-23} s.

2.1.2 Units of Energy and Interaction Strength

The basic unit of energy in particle physics and cosmic ray physics is the electronvolt (eV). This is the kinetic energy gained by an electron by passing through a potential difference of 1 V. Different appropriate energy measures are obtained by scaling the eV in threefold order of magnitude units, i.e. a kiloelectronvolt (KeV) is 10^3 eV, megaelectronvolt (MeV) is 10^6 eV, (giga) GeV = 10^9 eV, (tera) TeV = 10^{12} eV, (peta) PeV = 10^{15} eV, (eta) EeV = 10^{18} eV and (zeta) ZeV = 10^{21} eV. The total particle energy and the kinetic energy $E_k = E - mc^2$ are measured in the same units. Particle momenta $p = (E^2 - m^2c^4)^{1/2}$ are measured in eV/c.

The interaction strength is measured by the interaction cross-section σ, which is expressed in units of area. The basic unit is the barn = 10^{-24} cm^2. Common units are the millibarn, 1 mb = 10^{-3} b and the microbarn, 1 μb = 10^{-6} b. Cross-sections are usually given per one nucleon (or nucleus) of target. If a particle has interaction cross-section of $\sigma = 1$ mb, its mean free path in a medium of nucleon density