Cosmic Rays in Magnetospheres of the Earth and other Planets

Astrophysics and Space Science Library

EDITORIAL BOARD

Chairman

W. B. BURTON, *National Radio Astronomy Observatory, Charlottesville, Virginia, U.S.A.* (bburton@nrao.edu) and *University of Leiden, The Netherlands* (burton@strw.leidenuniv.nl)

F. BERTOLA, *University of Padua, Italy*

J. P. CASSINELLI, *University of Wisconsin, Madison, U.S.A.*

C. J. CESARSKY, *European Southern Observatory, Garching bei München, Germany*

P. EHRENFREUND, *Leiden University, The Netherlands*

O. ENGVOLD, *University of Oslo, Norway*

A. HECK, *Strasbourg Astronomical Observatory, France*

E. P. J. VAN DEN HEUVEL, *University of Amsterdam, The Netherlands*

V. M. KASPI, *McGill University, Montreal, Canada*

J. M. E. KUIJPERS, *University of Nijmegen, The Netherlands*

H. VAN DER LAAN, *University of Utrecht, The Netherlands*

P. G. MURDIN, *Institute of Astronomy, Cambridge, UK*

F. PACINI, *Istituto Astronomia Arcetri, Firenze, Italy*

V. RADHAKRISHNAN, *Raman Research Institute, Bangalore, India*

B. V. SOMOV, *Astronomical Institute, Moscow State University, Russia*

R. A. SUNYAEV, *Space Research Institute, Moscow, Russia*

Lev Dorman

Cosmic Rays in Magnetospheres of the Earth and other Planets

Prof. Lev I. Dorman
Head of Israel Cosmic Rays & Space Weather Center
and Emilio Sgre Observatory, affiliated to Tel Aviv University
and Israel Space Agency, Israel;
Chief Scientist of Cosmic Ray Department of N.V. Pushkov IZMIRAN
Russian Academy of Sciences, Troitsk, Russia
P.O. Box 2217
Qazrin 12900, Israel
lid@physics.technion.ac.il

Picture on cover: From Chapter 7, Section 7.8, paper of Flckiger et al. (2006). Courtesy of R. Btikofer and E. Flckiger.

ISBN: 978-1-4020-9238-1 e-ISBN: 978-1-4020-9239-8
DOI: 10.1007/978-1-4020-9239-8

Library of Congress Control Number: 2008944237

 2009 Springer Science+Business Media B.V.

No part of this work may be reproduced, stored in a retrieval system, or transmitted in any form or by any means, electronic, mechanical, photocopying, microfilming, recording or otherwise, without written permission from the Publisher, with the exception of any material supplied specifically for the purpose of being entered and executed on a computer system, for exclusive use by the purchaser of the work.

Cover design: eStudio Calamar S.L.

Printed on acid-free paper

9 8 7 6 5 4 3 2 1

springer.com

Dedicated to the memory of my teachers both in science and in life: Professor, Academician Eugenie Lvovich Feinberg (in the former USSR, Physical Lebedev Institute) and Minister of Science of State Israel, Director of Advanced Study Institute of Tel Aviv University, President of Israel Space Agency, Professor Yuval Ne'eman

**Eugenie Lvovich
Feinberg (1912–2005)**

**Yuval Ne'eman
(1925–2006)**

Preface

The problem of cosmic ray (CR) geomagnetic effects came to the fore at the beginning of the 1930s after the famous expeditions by J. Clay onboard ship (*Slamat*) between the Netherlands and Java using an ionization chamber. Many CR latitude expeditions were organized by the famous scientists and Nobel Laureates R. Millikan and A. Compton. From the obtained latitude curves it follows that CRs cannot be gamma rays (as many scientists thought at that time), but must be charged particles. From measurements of azimuthally geomagnetic effect at that time it also followed that these charged particles must be mostly positive (see Chapter 1, and for more details on the history of the problem see monographs of Irina Dorman, M1981, M1989).

The first explanations of obtained results were based on the simple dipole approximation of the geomagnetic field and the theory of energetic charged particles moving in dipole magnetic fields, developed in 1907 by C. Störmer to explain the aurora phenomenon. Let us note that it was made about 5 years before V. Hess discovered CRs, and received the Nobel Prize in 1936 together with K. Anderson (for the discovery of CR and positrons in CR). Störmer's theory, based only on the first, dipole harmonic of the earth's internal magnetic field, played an important role for many years in the explanation of the basic properties of CR geomagnetic effects (see Chapter 2), and is usually used even today for rough estimations of geomagnetic cutoff rigidities and behavior of trapped radiation in the earth's magnetosphere. This theory, developed by G. Lemaître and M.S. Vallarta, extended the conception of Störmer's cone of forbidden trajectories and introduced the conception of CR allowed cone with the existence of a penumbra region between these cones. From Störmer's theory it follows, for example, that minimal CR intensity line on the earth, so-called CR equator, must coincide with the geomagnetic equator in dipole approximation. However, detailed experimental investigations of CR latitude effect along different meridians show that there are sufficient differences between CR and geomagnetic equators caused by important influence of higher harmonics of the geomagnetic field on CR energetic particles moving in that geomagnetic field. Moreover, besides internal sources of the geomagnetic field also are important external sources caused by different currents in the earth's magnetosphere.

Several analytical and numerical methods for CR trajectory calculations were developed for determining cutoff rigidities for vertical and oblique directions at different zenith and azimuth angles, effective and apparent cutoff rigidities, effective asymptotic directions, impact zones, and acceptance cones in the real geomagnetic field including the higher harmonics (see Chapter 3). This chapter is based not only on original papers of the author and his colleagues N.G. Asaulenko, V.S. Smirnov, and M.I. Tyasto, but also on key works of P. Bobik, E.O. Flückiger, M. Kodama, I. Kondo, K. Kudela, K.G. McCracken, J.J. Quenby, E.C. Ray, M.A. Shea, D.F. Smart, M. Storini, I. Usoskin, W.R. Webber, G.J. Wenk, and many others who calculated these important parameters for CR behavior in the earth's magnetosphere. Especially important are calculations during 1960–1970s of effective cutoff rigidities for vertical direction and effective asymptotic directions for all CR stations of the worldwide network by K.G. McCracken, M.A. Shea, and D.F. Smart (McCracken et al., M1962, M1965; Shea et al., M1965, M1976; Shea and Smart, M1975). M.A. Shea and D.F. Smart also regularly published articles every 5 years, starting from the epoch 1955.0 up to the present time, on data regarding 5° latitude $\times 15^\circ$ longitude world grids of trajectory-derived effective vertical cutoff rigidities.

Theoretical results obtained in Chapter 3 were checked in many CR latitude surveys during the Japanese expeditions during 1956–1962 to Antarctica; in Sweden–USA latitude surveys during 1956–1959 in connection with International Geophysical Year; in Canadian expeditions during 1965–1966; in neutron monitor surveys in the Southern Ocean by USA, South Africa, and Australia; in latitude surveys of environmental radiation and soft secondary CR components by Italian expeditions to Antarctica; in annual CR latitude summer surveys over the territory of the former USSR during 1964–1982; in CR planetary surveys by USSR expeditions on the ships *Kislovodsk* and *Academician Kurchatov*; in South African latitude surveys on different altitudes from airplanes; and many CR latitude surveys on balloons and satellites (see Chapter 4). In this chapter we consider also: (1) the problem on CR latitude knee mainly in the frame of the key works by O.C. Allkofer and W.D. Dau, (2) CR latitude–altitude dependencies in the frame of the key work by A.V. Belov and colleagues, and (3) daily CR intensity dependencies from cutoff rigidity in the frame of key works by F. Bachelet and colleagues. Let us note that experimental data obtained in many CR expeditions during about 80 years are unique because the geomagnetic field changes sufficiently with time and consequently causes changes in planetary distributions of cutoff rigidities, asymptotic directions, and acceptance cones.

An example of detail analysis of CR latitude survey data obtained in the Italian expedition to Antarctica during 1996–1997 taking into account many different data, exact corrections on meteorological factors, CR worldwide variations, CR North–South and Forward–Backward asymmetries, exact account of oblique CR arriving in calculations of apparent cutoff rigidities along the latitude survey, and some other exact corrections are described in Chapter 5 based mainly on original works of Dorman and his colleagues O.A. Danilova, N. Iucci, M. Parisi, N.G. Ptitsyna, M.I. Tyasto, and G. Villorresi. This analysis made possible the finding of coupling functions for standard neutron monitors and for neutron counters without lead with the highest accuracy at present time.

Geomagnetic time variations of CR intensity (caused by variations of cutoff rigidities) are determined by internal and magnetospheric sources (see Chapter 6). This chapter considers the trajectory calculations of long-term variations of planetary distribution of cutoff rigidities caused mainly by internal source during the last 2,000 years, during 1600–2000 in steps of 50 years, and during 1950–2005 in steps of 5 years based mainly on key papers of M.A. Shea, D.F. Smart, and E.O. Flückiger. CR geomagnetic variations of magnetospheric origin were discovered in detailed investigations of CR Forbush-decreases during the main phase of great magnetic storms, when at middle latitude stations CR intensity increase caused by decrease of cutoff rigidity was observed. Through many investigations it was established that this decrease of cutoff rigidity is mainly caused by sufficient increase of ring current from about 10^6 A in quiet periods up to about 10^7 A during the main phase of a strong geomagnetic storm (the same phenomenon caused moving of aurora boundary to low latitudes, up to Egypt, in periods of big magnetic storms). CR variations of magnetospheric origin were investigated in detail theoretically and experimentally in key papers by H. Debrunner, E.O. Flückiger, M. Kodama, S. Kudo, T. Makino, T. Obayashi, P. Tanskanen, M.A. Shea, D.F. Smart, and M. Wada, as well as in papers of Dorman and his colleagues L.G. Asaulenko, L.M. Baisultanova, A.V. Belov, V.M. Dvornikov, V. Sdobnov, A.V. Sergeev, M.I. Tyasto, and V.G. Yanke. This chapter also shows that by using CR data inverse problems and estimated time variations of main parameters of ring current and other magnetospheric current systems during big magnetic storms may be solved.

In the last 20 years sufficient jumps were made in our understanding of the earth's magnetospheric structure for different disturbance levels, thanks to key papers by N.A. Tsyganenko and his colleagues M.I. Sitnov and A.V. Usmanov, who developed magnetospheric models on the basis of a lot of satellite and ground observation data. The main matter of Chapter 7 is based on crucial results of Tsyganenko and on key papers which checked these results, and some other magnetospheric models by galactic and solar CR observations (see Contents and References for Chapter 7).

In Chapter 8 we consider very short atmospheric and magnetospheric effects of CR in other planets. It is a pity that this problem up to now is only weakly developed. We do not find any papers in scientific literature devoted to the problem of CR behavior in atmospheres and magnetospheres of other planets and satellites, except two papers of Dorman and colleagues which consider only the planets Venus, Mars, and Jupiter. However, we hope that in the near future this problem will receive higher attention of CR scientists and will be developed to a level comparable with the level of research on our planet.

Let me note, that in this book, as in the previous two (Dorman, M2004 and M2006), I often use extended nomination of CRs as particles with energy much bigger than average energy of background plasma's particles. It means that we have extragalactic CR, galactic CR, solar CR, anomaly CR, interplanetary CR, and magnetospheric CR (there are also outer CR and local CR; for details, see Dorman, M2004, Chapter 1). Scientific literature often uses nomination energetic particles for CRs generated on the sun, in interplanetary space and in magnetospheres of the earth and other planets and their satellites.

The behavior of galactic, solar, and anomaly CRs in the planetary magnetospheres are determined not only by main planetary magnetic fields but also by very variable magnetospheric currents caused by drifts of local CR (energetic particles) in radiation belts and plasma processes from solar wind–magnetosphere interactions as well as interplanetary shock waves–magnetosphere interactions during substorms and magnetic storms. On the other hand, main sources of radiation belts are caused by interactions of galactic, solar, anomaly, and interplanetary CRs with upper atmosphere causing the formation of albedo and acceleration local CRs in many processes inside magnetospheres. So there are really very complicated non-linear interactions of CR, solar wind, and interplanetary shock waves with planetary magnetospheres.

The detailed Contents give information on the problems considered and discussed in the monograph. At the beginning of this monograph, there is a list of Frequently used Abbreviations and Notations. At the end of the book, in the Conclusion and Problems, we summarize the main results and consider some unsolved key problems, which are important for the development of the considered branch of research. In the References there are separate lists for Monographs and Books (with years starting by the letter M) as well as for each chapter. For the convenience of the reader, we have also prepared a Subject Index. At the end of the book there are Appendices, where we have placed big tables and complicated colored figures; ith labels starting with the letter A.

I would be grateful for any comments, suggestions, preprints, and reprints that can be useful in our future research, and can make the next edition of the book better and clearer. They may be sent directly to me by e-mail (lid@physics.technion.ac.il; lid010529@gmail.com), by fax [+972] 4 696 4952, or by post to the following address: Prof. Lev I. Dorman, Head of ICR&SWC and ESO, P.O. Box 2217, Qazrin 12900, ISRAEL.

July 2008
Qazrin, Moscow, Princeton

Lev I. Dorman

Acknowledgments

As a sign of my heartfelt gratitude, this book is dedicated to the memory of my teachers, both in science and in life: Eugenie Lvovich Feinberg, in former USSR, and Yuval Ne'eman, in Israel.

It is my great pleasure to cordially thank the authors of papers and monographs reflected and discussed in this book, and my former students who became colleagues and friends: for many years of collaboration and interesting discussions – M.V. Alania, R.G. Aslamazashvili, V.Kh. Babayan, M. Bagdasariyan, L. Baisultanova, V. Bednaghevsky, A.V. Belov, A. Bishara, D. Blenaru, Ya.L. Blokh, A.M. Chkhetia, L. Churunova, T.V. Dzhapiashvili, E.A. Eroshenko, S. Fisher, E.T. Franzus, L. Granitskij, R.T. Gushchina, O.I. Inozemtseva, K. Iskra, N.S. Kaminer, V.L. Karpov, M.E. Katz, T.V. Kebuladse, Kh. Khamirzov, Z. Kobilinsky, V.K. Koiava, E.V. Kolomeets, V.G. Koridse, V. Korotkov, V.A. Kovalenko, Yu.Ya. Krestyannikov, T.M. Krupitskaja, A.E. Kuzmicheva, A.I. Kuzmin, I.Ya. Libin, A.A. Luzov, N.P. Milovidova, L.I. Miroshnichenko, Yu.I. Okulov, I.A. Pimenov, L.V. Raichenko, L.E. Rische, A.B. Rodionov, O.G. Rogava, A. Samir Debish, V.S. Satsuk, A.V. Sergeev, A.A. Shadov, B. Shakhov, L.Kh. Shataashvili, G.Sh. Shkhalakhov, V.Kh. Shogenov, V.S. Smirnov, M.A. Soliman, F.A. Starkov, M.I. Tyasto, V.V. Viskov, V.G. Yanke, K.F. Yudakhin, A.G. Zusmanovich; for many years of support of our research in the former USSR and in Russia – Alexander Evgenievich Chudakov, Georgy Borisovich Khristiansen, Vladimir Kuznetsov, Vladimir Vladimirovich Migulin, Michael Dmitrievich Millionshikov, Vladimir Nikolaevich Oraevsky, Nikolai Vasil'evich Pushkov, Irena Vjacheslavovna Rakobolskaya, Sergei Nikolaevich Vernov, Georgy Timofeevich Zatsepin; for interesting discussions and fruitful collaboration – H.S. Ahluwalia, T.M. Aleksanyan, V.V. Alexeenko, I.V. Alexeev, H. Alfvén, E.E. Antonova, W.I. Axford, J.H. Allen, G.A. Bazilevskaja, G. Bella, N.P. Ben'kova, M. Bercovitch, E.G. Berezhko, V.S. Berezinsky, J.W. Bieber, R.C. Binford, S.P. Burlatskaya, G. Cini Castagnoli, A.N. Charakhchyan, T.N. Charakhchyan, A. Chilingarian, J. Clem, E. Cliver, H. Coffey, J.W. Cronin, I. Daglis, E. Daibog, A. Dar, R. Davis, Jr., H. Debrunner, V.A. Dergachev, V.A. Dogiel, A.Z. Dolginov, S.S. Dolginov, I.V. Dorman, L.O.C. Drury, M. Duldig, V.M. Dvornikov, D. Eichler, E. Etzion, Yu.I. Fedorov, P. Ferrando, E.O. Fluckiger, V. Fomichev,

M. Galli, A.M. Galper, Yu.I. Galperin, V.L. Ginzburg, E.S. Glokova, N.L. Grigorov, O.N. Gulinsky, A.V. Gurevich, S.R. Habbal, J.E. Humble, N. Iucci, R. Kallenbach, G.S. Ivanov-Kholodny, G.E. Kocharov, I.D. Kozin, O.N. Kryakunova, G.F. Krymsky, K. Kudela, L.V. Kurnosova, V. Kuznetsov, A.A. Lagutin, A. Laor, A.K. Lavrukhina, Yu.I. Logachev, C. Lopate, H. Mavromichalaki, K.G. McCracken, B. Mendoza, M.A. Mogilevsky, I. Moskalenko, Y. Muraki, M. Murat, K. Mursula, V.S. Murzin, N. Nachkebia, K. Nagashima, G.M. Nikolsky, S.I. Nikolsky, V. Obridko, J. Pap, E.N. Parker, M. Parisi, S.B. Pikelner, L.P. Pitaevsky, M.K.W. Pohl, A. Polyakov, M.S. Potgieter, C. Price, N.G. Ptitsyna, V.S. Ptuskin, L.A. Pustil'nik, R. Pyle, A.I. Rez, S.I. Rogovaya, I.L. Rozental, S. Sakakibara, N. Sanchez, V. Sarabhai, I.A. Savenko, K. Scherer, V. Sdobnov, V.B. Semikoz, V.P. Shabansky, Yu.G. Shafer, G.V. Shafer, M.M. Shapiro, P.I. Shavrin, M.A. Shea, I.S. Shklovsky, Ya. Shwarzman, B.I. Silkin, J.A. Simpson, G.V. Skripin, D.F. Smart, A. Somogyi, T. Stanev, M. Stehlic, A. Sternlieb, P.H. Stoker, M. Storini, Yu.I. Stozhkov, A. Struminsky, A.K. Svirzhevskaya, S.I. Syrovatsky, P.J. Tanskanen, A.G. Tarkhov, I. Transky, V.A. Troitskaya, B.A. Tverskoy, I.G. Usoskin, J.F. Valdes-Galicia, E.V. Vashenyuk, P. Velinov, D. Venkatesan, S.N. Vernov, E.S. Vernova, G. Villoresi, T. Watanabe, J.P. Wefel, G. Wibberenz, A.W. Wolfendale, V. Yakhot, G. Yom Din, A.K. Yukhimuk, N.L. Zangrilli, G.T. Zatsepin, G.B. Zhdanov, V.N. Zirakashvili, I.G. Zukerman; for constant support and the kind-hearted atmosphere during my education and long journey in science, my parents Isaac (1884–1954) and Eva (1894–1958), wife Irina, daughters Maria and Victoria, sisters Maria Tiraspolskaya and Mara Pustil'nik, brothers Abraham Argov (1914–2003) and Zuss (1916–1958), parents-in-law Olga Ivanovna Zamsha and Vitaly Lazarevich Ginzburg, son-in-law Michael Petrov, relatives in Israel – cousins Michal, David, Shlomo, Dickla, and nephews Raja, Ada, Lev, Dan, Dalia, Shlomo; for great help and collaboration in the period of my work in Israel which made it possible to continue the research on CRs – Yuval Ne'eman, Abraham Sternlieb, Aby Har-Even, Isaac Ben Israel, Zvi Kaplan, Lev Pustil'nik, Igor Zukerman, Michael Murat, Alexei Zusmanovich, Lev Pitaevsky, David Eichler, Matilda Elron, Ronit Nevo, Shushana Shalom, Sami Bar-Lev, Avi Gurevich, Nunzio Iucci, Giorgio Villoresi, Mario Parisi, Marisa Storini, John A. Simpson, W.I. Axford, Arnold W. Wolfendale, Victor Yakhot, Alexander Polyakov, Doraswamy Venkatesan, Harjit Ahluwalia, Jose F. Valdes-Galicia, Yasushi Muraki, Marc Duldig, Heleni Mavromichalaki, Anatoly Belov, Victor Yanke, Eugenia Eroshenko, Natalie Ptitsyna, Marta Tyasto, Olga Kryakunova; for great help in preparing many figures and full references – Igor Zukerman; for fruitful advice and help in preparing the manuscript – Ramon Khanna, Sonja Japenga, Vaska Krabbe, Kirsten Theunissen, and language editor Richard Freeman; the work of the Israeli-Italian Emilio Segrè Observatory is supported by the Collaboration of Tel Aviv University (ISRAEL) and “Uniroma Tre” University and IFSN/CNR (ITALY) – my sincere gratitude for foundation and supporting of this collaboration – Nunzio Iucci, Yuval Ne'eman, Mario Parisi, Lev Pustil'nik, Abraham Sternlieb, Marisa Storini, Giorgio Villoresi, Igor Zukerman.

Contents

Frequently used Abbreviations and Notations	xxxiii
1 First Measurements of Cosmic Ray Geomagnetic Effects and the Problem of CR Nature	1
1.1 The First Measurements of CR Latitude Effect in Expeditions from Holland to Java and Problems in their Interpretation	1
1.2 The First Correct Explanation of CR Latitude Survey Results and Nature of CR; Compton and Millikan's CR Latitude Surveys	2
1.3 The First Determination of Planetary Distribution of CR Intensity at Sea Level; Longitude Geomagnetic Effect	4
1.4 The First Measurements of the CR Latitude Effect in the Stratosphere	6
1.5 East–West CR Geomagnetic Effect and Determination of the Sign of Primary Charged Particles	6
2 Cosmic Rays in the Dipole Geomagnetic Field	9
2.1 Dipole Approximation of Geomagnetic Field and Geomagnetic Equator	9
2.1.1 Polar Aurora and Störmer's Theory	9
2.1.2 Equations for Particle Moving in Dipole Field and their Integrals	9
2.2 Principles of Störmer's Theory	12
2.3 Störmer's Cone of Forbidden Trajectories	15
2.4 Lemaitre and Vallarta CR Allowed Cones in the Dipole Geomagnetic Field; Existence of Penumbra Region	17
2.5 Drift Hamiltonian for a Dipole Magnetic Field	18
2.5.1 The Matter of Problem	18
2.5.2 Drift Hamiltonian	18
2.5.3 Three Cases of the Choice of Parameters	19
2.5.4 The Conditions for Drift Approximation	21

2.6	Symplectic Method for the Tracing of CR Particle Motion in a Dipole Magnetic Field	21
2.6.1	The Matter of Problem	21
2.6.2	Hamiltonian Description of Energetic Charged Particle Motion in a Dipole Magnetic Field	23
2.6.3	Symplectic Integration Method of Calculations	25
2.6.4	Comparison with the Standard Runge–Kutta Method	27
2.6.5	Main Results and Discussion	28
2.7	Effective Cutoff Rigidity in Dipole Approximation	29
2.8	Checking of Dipole Model by Measurements of CR Equator	32
2.9	The Checking of Dipole Model by Direct Cutoff Rigidity Measurements	34
2.10	Checking of Dipole Model by Data on CR Variations	35
2.11	Initial Interpretations of the Differences Between CR and Geomagnetic Equators	35
2.12	Impact Zones, Asymptotic Directions, and Acceptance Cones in the Dipole Magnetic Field	36
2.13	Seasonal and Daily Variation of the Position of Impact Zones in Dipole Approximation	41
2.14	Asymptotic Accepted Cones and Expected Counting Rates of CR Detectors; Focusing Properties of Geomagnetic Field	42
3	Cosmic Rays in the Real Geomagnetic Field	51
3.1	Inner and Outer Sources of the Real Geomagnetic Field; Changing in Time	51
3.2	Presentation of the Real Geomagnetic Field by Series of Spherical Harmonics; Gauss Coefficients	52
3.3	Relative Role of Spherical Harmonics in the Formation of the Geomagnetic Field from Internal Sources	55
3.4	Analytical Methods of Trajectory Calculations in the Real Geomagnetic Field	56
3.4.1	General Equation	56
3.4.2	Störmer Method	57
3.4.3	Alfvén Method	60
3.4.4	Peculiarities at High Latitudes; Using Boltzmann Equation	63
3.4.5	The Case of High CR Energy Density in the Outer Magnetosphere and the Self-Consistent Nonlinear Problem	63
3.4.6	Regions of Applicability of Analytical Methods	64
3.5	Main Methods of Numerical Calculation of Charged-Particle Trajectories in the Real Geomagnetic Field	64
3.5.1	Gauss Coefficients and Expected Accuracy of Numerical Calculation of Trajectories in the Real Geomagnetic Field; Comparison with that Expected for Dipole Field	64

3.5.2	Störmer's Method of Numerical Calculation of Trajectories in Dipole Geomagnetic Field: Why it cannot be Used for Real Geomagnetic Field	67
3.5.3	Method Runge–Kutta of Fourth Order for Numerical Calculations of CR Trajectories in Real Geomagnetic Field	67
3.5.4	The Choice of the Value of the Step of Numerical Integration: The Gill's Modification	69
3.5.5	Kelsall's Modification of the Runge–Kutta Method	70
3.5.6	The Merson's Modification of the Runge–Kutta Method	70
3.5.7	The Stability of CR Trajectory Integration and Control of Accuracy	71
3.5.8	Numerical CR Trajectory Integration in Spherical Geographical System of Coordinates	72
3.5.9	Divergence-Free Magnetic Field Interpolation and Symplectic Method of Charged-Particle Trajectory Integration	75
3.5.10	Symplectic Tracing of High-Energy Charged Particles in the Inner Magnetosphere	77
3.6	Asymptotic Directions, Impact Zones, and Acceptance Cones in the Geomagnetic Field Including the Higher Harmonics	85
3.6.1	Examples for Different CR Stations	85
3.6.2	Classification of Stations by their Acceptance Cones . . .	86
3.6.3	Acceptance Cones for Russian and Former Soviet Net of Stations	88
3.6.4	Asymptotic Directions for the Worldwide Net of CR Stations	90
3.6.5	Asymptotic Directions for Solar CR During Some Great Events	90
3.6.6	Asymptotic Directions for Several Selected CR Stations	90
3.7	On the Connection of CR Cutoff Rigidities in the Real Geomagnetic Field with the L -Parameter of McIlwain	92
3.7.1	Results for Dipole Field	92
3.7.2	Results for Trajectory Calculations for Quiet Time	93
3.7.3	Using the Relation between R_c and McIlwain L -Parameter for Estimation of R_c Variations during Disturbed Periods	98
3.7.4	Estimation of R_c for Any Altitude on the Basis of the Relationship Between R_c and L	98
3.7.5	Global Rigidity Cutoff Maps Based on the Relation Between R_c and L	99
3.7.6	Calculations of R_c and L for Different Models: Comparison	101

3.8	Planetary Distribution of Cutoff Rigidities at Altitude 20 km	102
3.8.1	Offset Dipole and CR Cutoff Rigidity Coordinates	102
3.8.2	CR Vertical Cutoff Rigidity Planetary Distribution for the Epoch 1955.0	104
3.8.3	CR Vertical Cutoff Rigidity Planetary Distributions for Epochs 1965.0 and 1975.0	106
3.8.4	The Change of CR Vertical Cutoff Rigidity Planetary Distribution During 20 Years, from 1955 to 1975	106
3.8.5	CR Vertical Cutoff Rigidity Planetary Distribution for Epoch 1980	106
3.8.6	CR Vertical Cutoff Rigidity Planetary Distribution for Epoch 1990.0	106
3.8.7	CR Vertical Cutoff Rigidity Planetary Distribution for Epoch 1995.0	107
3.8.8	CR Vertical Cutoff Rigidity Planetary Distribution for Epoch 2000.0	107
3.9	CR Effective Cutoff Rigidity Planetary Distribution for Satellite Altitudes	107
3.10	Cutoff Rigidities for the Worldwide Network of CR Stations	109
3.10.1	Calculations of Cutoff Rigidities for CR Stations and Checking by Data on CR Variations	109
3.10.2	Comparison of Different Models of Calculation	110
3.10.3	Comparison of Different Models of the Geomagnetic Field	111
3.10.4	Cutoff Rigidities for Inclined Directions	111
3.11	The CR Penumbra Effects in the Real Geomagnetic Field	111
3.11.1	The CR Penumbra in Dependence of Delineated Value	111
3.11.2	The Concept of the First Forbidden Band in the CR Penumbra	113
3.11.3	Penumbra Width in Dependence of Vertical Cutoff Rigidity for Different Epochs	114
3.11.4	Effective Vertical Cutoff Rigidities for Different CR Detectors and Types of CR Variations	114
3.12	CR Rigidity Transmittance Functions	119
3.12.1	The Concept of the Transmittance Function and Two Methods of Calculation	119
3.12.2	The Dependence of Transmittance Function Calculation Accuracy from the Delineated Value	121
3.12.3	The Dependence of Transmittance Function Calculation Accuracy from the Number of Azimuthal Directions	122
3.12.4	On the Influence of Ionization Losses on the Transmittance Function	122

3.12.5	On the Checking of the Theoretically Calculated CR Rigidity Transmittance Functions by Balloon Experiments	125
3.12.6	On Checking the Theoretically Calculated CR Rigidity Transmittance Functions by Satellite Experiments	128
3.12.7	Transmittance Function Approach to Disentangle Primary from Secondary CR Fluxes in the Penumbra Region	129
3.13	Obliquely Incident Particles and Apparent Cutoff Rigidities	136
3.14	Simulation of the Geomagnetic Cutoff Rigidity Angle Distribution with the GEANT-3 Computing Program using the Data of the International Geomagnetic Reference Field	140
3.14.1	Importance of the Exact Knowledge of the CR Cutoff Rigidity Angle Distribution for the Problems of Atmospheric Neutrino and Other Secondary Particles Generated in the Earth's Atmosphere	140
3.14.2	Using the Backtracking Method for the Precise Calculation of the Geomagnetic Cutoff Rigidities	141
3.14.3	Calculations and Results for the Planetary and Angle Distributions of CR Geomagnetic Cutoff Rigidity	142
3.14.4	Comparison with AMS Measurements of the Geomagnetic Cutoff on Shuttle	143
3.15	Geomagnetic Field Influence on Secondary CR Generated and Propagated in the Atmosphere	144
3.15.1	On the Possible Geomagnetic Effects in Secondary CRs	144
3.15.2	The Main Conditions for Calculations and Principal Sources	144
3.15.3	Expected Ratios of Secondary CR Neutrons to Muons with and without Allowance for the Geomagnetic Field	145
3.15.4	Expected Differential Energy Spectra $N(E)$ of Secondary Neutrons and Muons at Sea Level and at $H = 5\text{ km}$ from Primary CR Protons with Energy 3 and 10 GeV According to Calculations with and Without Geomagnetic Field Influence on Their Propagation in the Atmosphere	147
3.15.5	Differential Energy Spectra of Neutrons, Protons, Charged Pions and Muons at Sea Level and Altitudes 5, 10, 15 km Generated from Primary Protons with Energies 3 and 10 GeV According to Calculations Taking into Account the Geomagnetic Field Influence on Secondary CR Particles Propagation	148
3.15.6	On the Detector's Integral Multiplicity Taking Account of Geomagnetic Field Influence on Secondary CR Particle Propagation	149

3.15.7	On Checking Geomagnetic Field Effects on Secondary CRs During their Propagation in the Atmosphere using Data from High-Latitude CR Stations	150
3.16	On the Influence of IMF on the CR Entry into the Earth's Magnetosphere	151
3.16.1	The Matter of Problem	151
3.16.2	The MHD Model of the Magnetosphere for Different IMF Conditions	151
3.16.3	Calculations of CR Particle Trajectories	154
3.16.4	Particle Distribution in Velocity Space	155
3.16.5	How the Magnetosphere Reaches a Quasi-Steady Configuration Consistent with Each IMF Direction	156
3.16.6	Calculation Results for IMF in a Southward Orientation	156
3.16.7	Calculation Results for IMF in a Dawnward Orientation	159
3.16.8	Calculation Results for IMF in a Northward Orientation	161
3.16.9	Comparison of the Time-Dependent and Time-Independent Cases	164
3.16.10	On the Energy Change of Particles Entering Inside the Magnetosphere	166
3.16.11	Demonstration of the Magnetospheric Configuration's Control of the Entry of High-Energy Particles	170
3.16.12	On the ^3He Ion Trajectories for Southward IMF	173
3.16.13	Main Results and Discussion	173
3.17	Propagation of Protons in the Energy Range 0.1–50 MeV through the Earth's Bow Shock, MagnetoSheath, and Magnetopause Inside the Magnetosphere	174
3.17.1	The Matter of Problem	174
3.17.2	Three Categories of Energetic Protons Incoming to the Earth	175
3.17.3	Energetic Proton Propagation through Bow Shock with Shock-Drift Acceleration	176
3.17.4	Energetic Particles Propagation through Bow-Shock with Diffusive Shock Acceleration	177
3.17.5	MHD Simulation	177
3.17.6	The Grid System for Simulation	178
3.17.7	The Efficiency of the Shock-Drift Acceleration	178
3.17.8	Calculation of Proton Trajectories for Three Regions . . .	179
3.17.9	Results for the Shock-Drift Acceleration at the Bow Shock (Case A)	180
3.17.10	Energetic Particle Entry into the Magnetosphere and Expected Polar Map of Proton Precipitation at $4r_e$ (Case A)	182

3.17.11	Relation Between Proton Entry and Shock-Drift Acceleration.....	184
3.17.12	Statistical Results for Proton Entry and Shock-Drift Acceleration.....	187
3.17.13	Results for Large Solar Wind Density Increase (Case B).....	187
3.17.14	Comparison Between Cases A and B.....	187
3.17.15	Discussion on the Main Results and Observational Evidence.....	189
4	Cosmic Ray Planetary Surveys on Ships, Trains, Tracks, Planes, Balloons, and Satellites.....	191
4.1	CR Latitude Surveys by Japanese Expeditions during 1956–1962 to Antarctica on the Ship Soya.....	191
4.1.1	The Routes and CR Apparatus in Japanese and Some Previous Latitude Surveys.....	191
4.1.2	Corrections of Japanese CR Latitude Survey Data on the Barometric Effect and Worldwide CR Variations.....	191
4.1.3	Database of Japanese CR Latitude Surveys.....	194
4.1.4	Geomagnetic Latitude CR Curves for Neutron and Muon Components.....	195
4.1.5	CR Equator According to Measurements in Japanese Expeditions.....	195
4.1.6	Longitude Effect Along the CR Equator.....	196
4.1.7	The Position of Latitude Knee According to Japanese Expeditions.....	197
4.1.8	Planetary Distribution of CR Neutron Intensity.....	197
4.2	Swedish–USA Latitude Surveys During 1956–1959 in Connection with the International Geophysical Year.....	198
4.2.1	Latitude Surveys and the Problem of CR Cutoff Rigidities.....	198
4.2.2	CR Equator Along the Longitude 14°W.....	200
4.2.3	Dependencies of CR Intensity from the Cutoff Rigidity.....	201
4.3	CR Latitude Surveys by Canadian Expeditions in 1965–1966 ...	201
4.3.1	Three Canadian CR Latitude Surveys, Routes, and using Apparatus.....	201
4.3.2	Main Results for the Expedition in Summer 1965.....	203
4.3.3	CR Latitude Survey in Canada in November–December 1965.....	203
4.3.4	CR Latitude Survey in Western USA and Hawaii in Summer 1966.....	204
4.3.5	Calibrated and Extended Measurements of CR Intensity on the Aircraft at Different Altitudes and at Different Cutoff Rigidities.....	206

4.3.6	Geographically Smoothed Geomagnetic Cutoffs Rigidities	207
4.3.7	Final Analysis of Three Canadian CR Latitude Survey Data	208
4.3.8	CR Latitude Effects at Different Altitudes	210
4.3.9	Comparison of Latitude Curves for Neutron Intensity in Two Minima of Solar Activity in 1954/55 and 1965/66	211
4.4	NM Surveys in the Southern Ocean to Antarctica by USA, Australia, and South Africa	212
4.4.1	Main Results of the Latitude Survey 1994/95; Discovery of the Sea State CR Effect	212
4.4.2	CR Spectra Deduced from Neutron Monitor Surveys ...	214
4.4.3	Apparent Geomagnetic Cutoffs and the CR Anomaly in the Cape Town Region	216
4.4.4	Using He-3 Neutron Counters for Neutron-Component Measurements; CR Latitude Survey in 1998/99	217
4.4.5	Latitude Survey Observations of Neutron Multiplicities	220
4.4.6	Continuing Each-Year NM Latitude Surveys: Main Results from 1994–2001	223
4.5	Latitude Surveys of Environmental Radiation and Soft Secondary CR Components by Italian Expeditions to Antarctica	225
4.5.1	Environmental Radiation and Soft Secondary CR Monitoring Along the Course of the Expeditions from Italy to Antarctica and Back	225
4.5.2	The Environmental Radiation and Soft Secondary CR Detectors	227
4.5.3	Measured Spectra of Environmental Radiation	228
4.5.4	Latitude Dependencies of Environmental Radiation in the 50–3,500 keV Energy Band	228
4.5.5	Observations of Transition Sea-to-Land Effects and “Radonic Storms” in the Environment Radiation During Latitude Surveys	230
4.5.6	Latitude Effects of the Soft Secondary CR Components in the Energy Ranges 2.8–5.0 and 5–20 MeV	231
4.5.7	The Main Results Obtained During Latitude Surveys of Environment Radiation and Soft Secondary CR Components	232
4.6	Daily CR Latitude Curves Derived from the NM Worldwide Network Data	232
4.6.1	The Main Idea of the Method Developed by Italian Scientists	232
4.6.2	The Daily Sea-Level CR Latitude Curves Obtained from the NM Worldwide Network and CR Latitude Surveys	233

4.6.3	Using CR Latitude Survey Data for NM Calibration . . .	234
4.6.4	Using Daily Sea-Level CR Latitude Curves for Studying Spectral Structure of Large Forbush Decreases	236
4.6.5	Using Daily Sea-Level CR Latitude Curves for Studying the Long-Term CR Spectral Variations	241
4.6.6	Comparison of CR Latitude Curves for Long-Term and Forbush Decreases in CR Spectral Variations	244
4.6.7	Using Daily Sea-Level CR Latitude Curves for Studying the Influence of the Primary CR Modulation on the Attenuation Coefficient of the Nucleonic Component at Different Latitudes and Altitudes	247
4.6.8	Using Daily CR Latitude Curves for Studying the Influence of the Primary CR Modulation on the Coupling Functions of the Nucleonic Component at Sea Level and at Altitudes $\sim 1,900m$ above Sea Level	248
4.6.9	Latitude and Altitude Dependencies of Primary Modulation Effects in Neutron Multiplicity Distribution in the NM-IQSY	250
4.7	CR Latitude Surveys over the Territory of the Former USSR . . .	254
4.7.1	CR Intensity Distribution over the Territory of the Former USSR	254
4.7.2	Latitude Curves of Neutron Intensity and Cutoff Rigidities	255
4.7.3	Coupling Functions for Neutron Component at Sea Level	256
4.7.4	Coupling Functions for the Neutron Component at Mountain Level	257
4.7.5	Calculation of the Integral Multiplicity for the Neutron Component	258
4.7.6	The Measurements of Geomagnetic Effects by CR Telescope; the Methods for Treating the Experimental Data	258
4.7.7	Cutoff Rigidities for CR Telescope: Vertical and Inclined Directions	260
4.7.8	Latitude Curves for the CR Telescope	261
4.7.9	Amplitudes of Latitude Effects of Various Components Measured by CR Telescope	262
4.7.10	The East–West CR Asymmetry	262
4.7.11	Coupling Functions and Integral Multiplicities for Total Ionizing and Hard CR Components Derived from Latitude Curves	264
4.7.12	Latitude Surveys and Coupling Functions for Neutron Monitor Without Lead	265

4.7.13	The Airplane CR Latitude Surveys over the Former USSR at Altitudes with Pressures of 260–400 mb	269
4.7.14	The Balloon CR Latitude Surveys over the Former USSR	270
4.7.15	The Balloon Measurements over the Former USSR of East–West CR Asymmetry: Estimation of the Upper Limit for Antiproton/Proton Ratio	271
4.8	Soviet CR Survey Expeditions over the World on the Ship <i>Kislovodsk</i>	275
4.8.1	CR Latitude Survey During December 1967–March 1968	275
4.8.2	Determining the Coupling Functions	276
4.8.3	Determining the CR Equator at 28°W	277
4.9	Soviet CR Survey Expeditions over the World on the r/v Academician Kurchatov	278
4.9.1	Regular CR Latitude Measurements on the r/v Academician Kurchatov	278
4.9.2	Determining of Coupling Functions on the Basis of Latitude Surveys	279
4.9.3	The Normalizing of the Worldwide Network of CR Stations on the Basis of CR Latitude Surveys by r/v Academician Kurchatov	280
4.9.4	Determining Integral Multiplicities	281
4.9.5	Determining the Primary Spectrum of Long-Term CR Variation	283
4.9.6	Comparison of Coupling Functions Derived from CR Latitude Services with Theoretical Expected	284
4.9.7	Using CR Latitude Surveys by r/v Academician Kurchatov for Checking the Cutoff Rigidities Models	284
4.9.8	Estimation of Coupling Functions for Total Neutron Component and Different Multiplicities	286
4.9.9	Main Results of r/v Academician Kurchatov Expeditions in 1971/72 and 1975: Checking Cutoff Rigidities and Determining Coupling Functions	286
4.9.10	Main Results of the r/v <i>Academician Kurchatov</i> Expedition in 1982: Determining Coupling Functions for Without-Lead NM and for NM-IQSY Total Intensity and Different Multiplicities; Distribution Function of Multiplicities Depending on Cutoff Rigidity	290
4.10	CR Latitude–Altitude Surveys and Secondary CR Dependencies from Cutoff Rigidity and Atmospheric Depth	296
4.10.1	Latitudinal and Altitudinal Coupling Coefficients: Nominations and Interconnections	296
4.10.2	Latitude Dependence of Secondary CR Variations	298
4.10.3	Altitude Dependencies of Secondary Variations	299

4.10.4	Determination of the Spectrum of the Primary CR Variations	299
4.11	The Latitude Knee of Secondary CR	301
4.11.1	The Latitude Knee of Secondary CR and its Origin	301
4.11.2	The Calculation Model of the Secondary CR Knee Position	301
4.11.3	The Latitude Knee of the Nucleonic Component at Sea Level	302
4.11.4	The Latitude Knee of the Muon Component at Sea Level	304
4.11.5	The Altitude Dependence of the Knee for Nucleonic and Muon Components	304
4.12	Comparison with Observations on the CR Latitude Knee	306
4.12.1	Comparison for Neutron Component	306
4.12.2	Comparison for Muon Component at Sea Level	306
4.12.3	Comparison with Experimental Data on the CR Muon Latitude Knee at an Atmospheric Depth of 310 g/cm^2 ..	308
4.13	South African Latitude Surveys at Different Altitudes by Airplanes	311
4.13.1	South African Expeditions, Response Functions and 22-Year Modulation.....	311
4.13.2	Latitude Distributions of CR Components at Sea Level and at Airplane Altitudes in the South African Magnetic Anomaly	314
4.13.3	Cutoff Rigidities and Latitude Dependence of Muons at 307 g/cm^2 in Inclined Directions.....	318
4.14	Latitude CR Surveys on Balloons	322
4.14.1	Survey of CR Intensity in 86° N to 73° S Geomagnetic Latitude on Balloons.....	322
4.14.2	Latitude Surveys by Balloon Measurements of CR Vertical Intensity and East–West Asymmetry; Determining Energy Spectrum and Charge Sign of Primary CR	329
5	Main Results of Cosmic Ray Survey to Antarctica on the Ship <i>Itasca</i> in 1996/97	341
5.1	Description of Apparatus, Trajectory Calculations of Cutoff Rigidities in the Real Geomagnetic Field Along the Ship's Voyage.....	341
5.1.1	Importance of Obtaining Exact Data in CR Latitude Surveys	341
5.1.2	Principles of the Data Corrections Method	342
5.1.3	Description of the Experiment.....	343
5.1.4	The Recorded Data and Acquisition System	343

5.1.5	Quality Assurance Procedures: Presurvey and Postsurvey Measurements	344
5.1.6	The Latitude Survey: Route and Main Results	346
5.1.7	The Quality Assurance Procedures and Internal Tests . .	348
5.2	Correction for Primary CR Variations and Summary of All Corrections	349
5.2.1	Primary Isotropic Time Variations	349
5.2.2	Corrections for Primary North–South Asymmetry of CR Distribution in the Interplanetary Space	350
5.2.3	The Summing of all Corrections Including Meteorological Effects	352
5.2.4	Quality Assurance Procedure: Internal Comparison of Corrected Data	352
5.2.5	Critical Consideration of Results in Sections 5.1 and 5.2.1– 5.2.4	354
5.3	Computation of Cutoff Rigidities of Vertically Incident CR Particles for Latitude Survey	355
5.4	Dependencies of Corrected CR Intensities upon Cutoff Rigidity .	357
5.5	Forward–Backward Effect: CR East–West Asymmetry and Asymmetric Distribution of Neutron Absorption and Generation Around the Monitor	359
5.5.1	Forward–Backward Effect During CR Latitude Survey: Asymmetry in Cutoff Rigidities	359
5.5.2	Contribution of Nonvertical Incidence Particles to the 3NM-IQSY Counting Rate	360
5.5.3	Forward–Backward Effect During CR Latitude Survey: Expected Asymmetry in Neutron Intensities	362
5.6	CR Intensity Versus Cutoff Rigidity, Analytical Approximation, and Coupling Functions for the 3NM-IQSY and 2BC Detectors	364
5.6.1	Analytical Description of the Dependence of the 3NM-IQSY and 2BC Intensities on the Vertical Cutoff Rigidity	364
5.6.2	Analytical Description of Coupling Functions for the 3NM-IQSY and 2BC Detectors	365
5.7	Effective Cutoff Rigidities for Different Zenith and Azimuth Angles of CR Arriving at Points Along the Ship Route	365
5.7.1	Calculation of Effective Cutoff Rigidities for Different Zenith and Azimuth Angles of CR Arriving at Points Along the Ship Route from Italy to Antarctica	366
5.7.2	Effective Cutoff Rigidities for Different Zenith and Azimuth Angles for the Ship Route from Antarctica to Italy	369

5.8	Apparent Cutoff Rigidities Along the Ship's Route and Related Coupling Functions for the 3NM-IQSY and 2BC Detectors	371
5.8.1	Calculation of Apparent Cutoff Rigidities R_{cp}^{ap} along the Ship's Route: Dipole Approximation for Inclined Directions	371
5.8.2	Calculation of Apparent Cutoff Rigidities in the Real Geomagnetic Field for the Ship Route Italy–Antarctica Taking into Account Results of Trajectory Calculations for Inclined Directions	373
5.8.3	Calculation of Apparent Cutoff Rigidities in the Real Geomagnetic Field for the Ship Route Antarctica–Italy Taking into Account Results of Trajectory Calculations for Inclined Directions	375
5.8.4	Comparison of Latitude Dependencies and Coupling Functions for Effective R_{cp} and Apparent R_{cp}^{ap} Cutoff Rigidities	376
5.9	Summary of Results of the CR Latitude Survey on the Ship <i>Italica</i> in 1996/97, and Discussion on Coupling Functions	377
5.9.1	Main Results Obtained in CR Latitude Survey in 1996/97 on Board the Ship <i>Italica</i>	377
5.9.2	Comparison and Discussion on Coupling Functions	378
6	Geomagnetic Variations of Cosmic Rays	381
6.1	Two Main Sources of CR Geomagnetic Variations	381
6.2	CR Variations Expected for Large Long-Term Changes of the Geomagnetic Field	382
6.2.1	Expected CR Variations Caused by Changing of the Earth's Dipole Magnetic Moment	382
6.2.2	Variations of Geomagnetic Origin During the Last 2,000 Years	384
6.2.3	Secular Variations of the Cutoff Rigidities	385
6.3	Trajectory Calculations of Long-Term Variation of Planetary Distribution of Cutoff Rigidities	386
6.3.1	Results for 1600–2000 by Steps of 50 Years	386
6.3.2	An Example of Cutoff Variability on CR Station LARC During 1955–1995 in Connection with Geomagnetic “Jerks”	387
6.3.3	Long-Term Variations of the Planetary Distribution of Geomagnetic Rigidity Cutoffs During the Last 2,000 Years	395
6.3.4	On the Variation of the Earth's Magnetic Dipole Moment During 1600–2005	401
6.3.5	Long-Term Variation of the Planetary Distribution of the Geomagnetic Rigidity Cutoffs Between 1950 and 2000	401

6.4	Long-Term Change of Cutoff Rigidities and the Expected Change of CR Intensity Owed to Geomagnetic Field Variation	404
6.5	The Global Cutoff Rigidities and their Change During the Last 2,000 Years	405
6.6	Effects of Axially Symmetric Currents in the Magnetosphere: The Provisional Assessment of the Causes of Variations in Cutoff Rigidities During Magnetic Storms	406
6.6.1	Development of Models of the Axially Symmetric Current's Influence on CR Cutoff Rigidities	406
6.6.2	The CR Vertical Cutoff Rigidities in the Presence of a Thin Equatorial Ring Current	409
6.6.3	The CR Cutoff Rigidities for Obliquely Incident Particles in the Presence of a Thin Equatorial Ring Current	410
6.7	Influence of Current Sheets Surfaces on the CR Geomagnetic Cutoff Rigidities	416
6.7.1	Current Sheet in the Form of a Spherical Surface	416
6.7.2	Current Sheet Formed by Rotating the Line of Force of the Magnetic Dipole	417
6.8	The Effect of Volume Currents in the Radiation Belts (Akasofu and Chapman Model) on the CR Cutoff Rigidity	422
6.9	The Influence of Ring Currents on the Position of CR Impact Zones and Asymptotic Directions	423
6.10	Effect of Compression of the Magnetosphere (Current System in Eastern Direction) on CR Cutoff Rigidities	424
6.11	Effect of Compression of the Magnetosphere and Western Current Systems on CR Asymptotic Directions and the Acceptance Cones	426
6.12	Asymmetric Variations of the Magnetosphere and Diurnal CR Variations of Geomagnetic Origin	427
6.13	Oscillation of the Asymptotic Acceptance Cones	427
6.14	The First Observations of CR Variations Due to Changes in the Geomagnetic Field	432
6.14.1	Unusual Increases During Magnetic Storms	432
6.14.2	Application of the Method of Coupling Functions	436
6.14.3	The Latitude–Longitude Distribution of the CR Increase Effect of September 13, 1957	439
6.14.4	The Latitude–Longitude Distribution of the CR Increase Effect on February 11, 1958	441
6.14.5	Main Properties of the CR Intensity Increase During the Main Phase of a Magnetic Storm	444
6.14.6	Statistical Properties of the CR Increase Effect During the Main Phase of the Geomagnetic Storm	445
6.14.7	Possible Influence of Small Magnetic Perturbations on Cosmic Rays	447

6.14.8	Earlier Detection of the Effect of Compression of the Magnetosphere in Cosmic Rays	448
6.14.9	Earlier Direct Observations of the Cutoff Variations by Means of Measurements on Balloons and Satellites and from Polar Cap Absorptions	448
6.15	Variations of the Geomagnetic Field and Local CR Anisotropy ..	449
6.15.1	The Asymmetry in the Variation of the CR Cutoff Rigidity for East–West Directions in Ahmedabad and North–South Directions in Moscow	449
6.15.2	The Analysis of CR Cutoff Rigidity Asymmetry on the Basis of Directional Data in Capetown and Yakutsk, and NM Worldwide Network	451
6.15.3	The Main Results and Discussion on CR Cutoff Rigidity Asymmetry During Magnetic Storms	455
6.15.4	The Anomalous CR Diurnal Variation During the Main Phase of the Magnetic Storm of February 11, 1958	455
6.15.5	On the Nature of CR Anisotropy Asymmetry: Local and Non-local Sources	456
6.16	CR Lunar-Daily Variation and Tidal Effects in the Earth's Magnetosphere	458
6.16.1	The Discovery of Lunar-Daily CR Variation and Discussion on Its Possible Origin	458
6.16.2	Amplitude Modulation of CR Solar-Daily Wave by the 27-Day Effect and Formation of Spurious CR Lunar-Daily Variation	459
6.16.3	Formation of Spurious CR Lunar-Daily Variation by the Phase Modulation of CR Solar-Daily Wave with a Period of 27 Days	460
6.16.4	Checking on the Properties of 27-Day Modulation of CR Solar-Daily Variation	460
6.16.5	On the Possible Reality of the CR Lunar-Daily Variation	461
6.16.6	The Dependence of the CR Lunar-Daily Variation on the Relative Positions of the Sun, Moon, and Earth ..	462
6.16.7	Dependence of the CR Lunar-Daily Variation on Cutoff Rigidity	463
6.16.8	Main Conclusions and Discussion on the CR Lunar-Daily Variation in Connection with Possible Tidal Effects in the Earth's Atmosphere and Magnetosphere ..	464
6.17	The Influence of the Tail of the Earth's Magnetosphere on the CR Cutoff Rigidities	467
6.17.1	Main Properties of the Tail of the Magnetosphere	467
6.17.2	Probable Mechanism by Which the Earth's Magnetic Tail Influences the CR Cutoff Rigidities	468
6.17.3	Approximate Position of the Curves of Constant Threshold at High Latitudes	468

6.17.4	The Influence of the Earth's Magnetic Tail on the Trajectories of Protons with Energy 1.2 MeV ...	469
6.17.5	Channeling of Low-Energy Cosmic Rays in the Tail of the Earth's Magnetosphere	470
6.18	Discriminating CR Magnetospheric Variations from Observed CR Data by the Spectrographical Method	473
6.18.1	The Matter of Problem	473
6.18.2	Determining Cutoff Rigidity Change by the Spectrographic Method on the Basis of Single CR Observatory Data	476
6.18.3	Determining the Cutoff Rigidity Changes by the Spectrographic Method on the Basis of Data from Two CR Observatories (Case One and Three Components)	477
6.18.4	Determining the Cutoff Rigidity Changes in the Case of Two Components in the Each of the Two CR Observatories	478
6.18.5	Determining Planetary Cutoff Rigidity Changes Distribution on the Basis of Many CR Observatories' Data by the Spectrographic Method	479
6.18.6	An Example of Using the Spectrographic Method for Determining CR Geomagnetic Variations; Application to Ring Current (Events in May and June 1972)	482
6.19	Cutoff Rigidity Variations of European Mid-latitude Stations During the September 1974 Forbush Decrease	485
6.19.1	The Matter of Problem	485
6.19.2	Used Data and Main Characteristics of the Event	485
6.19.3	Results of Data Analysis	486
6.19.4	Main Results and Discussion	488
6.20	The Extraterrestrial and Geomagnetic Variations in CR During the Forbush Decreases of March 26, 1976	489
6.20.1	Observation Data	489
6.20.2	Comparison Between the $\Delta R_c(t)$ and D_{st} -Variations	489
6.20.3	Variations of ΔR_c on Different CR Stations and Dependence of ΔR_c on R_{co}	491
6.20.4	Estimation of Ring Current's Properties	492
6.21	Estimates of the Parameters of the Magnetospheric Ring Current During Magnetic Storms on the Basis of CR Data	493
6.21.1	The Matter of Problem and Observational Data	493
6.21.2	Analysis of Data in the Frame of Two Used Models of Ring Current	493
6.21.3	Main Results and Discussion	496
6.22	Interrelation Between Variations of the CR Cutoff Rigidity and the Geomagnetic D_{st} -Variation During Magnetic Storms	497

6.22.1	The Matter of Problem	497
6.22.2	Observational Data and Variations of R_c During Three Events	498
6.22.3	Discussion and Main Results	499
6.23	The CR Decreases at High Latitudes and Increases at Middle Latitudes During Magnetic Storms	500
6.23.1	The Cases When During Magnetic Storms at High Latitudes Observed CR Decreases but at Middle Latitudes CR Increases	500
6.23.2	Main Equations for the Extended Spectrographic Method	501
6.23.3	CR and Magnetic Parameters for Eight Selected Magnetic Storms	502
6.23.4	Estimation of the Current Ring Radius	502
6.24	Using the Simplest Version of the Global Spectrographic Method (BDY-Method) for Discriminating CR Magnetospheric Variations	505
6.24.1	The Matter of Problem and the Simplest Version of the Global Spectrographic Method	505
6.24.2	Magnetospheric Effects on CR During Forbush Decreases in August 1972	506
6.24.3	The Longitude and Latitude Dependences of the Geomagnetic Cutoff Rigidity Variations During Strong Magnetic Storms in May 25–26, 1967, December 17–18, 1971, and in August 4–5, 1972	509
6.24.4	Changes of CR Cutoff Rigidities During Great Magnetic Storms in May 1967, August 1972, and November 1991	514
6.24.5	On the Correction of CR Data on Geomagnetic Variations	518
6.25	Magnetospheric Currents and Variations of Cutoff Rigidities on October 20, 1989	518
6.25.1	The Matter of Problem	518
6.25.2	Procedure of CR Cutoff Rigidity Calculations	519
6.25.3	Applying to NM Data of Moscow, Kiev, and Rome	520
6.25.4	Estimation of Magnetospheric Currents	520
6.25.5	Recalculations of Cutoff Rigidity Changes	522
6.25.6	Checking Using Balloon and Satellite Measurements	524
6.25.7	Summary and Discussion	524
7	Magnetospheric Models and their Checking by Cosmic Rays	525
7.1	The Earth's Magnetic Field with a Warped Tail Current Sheet (Tsyganenko-89 Model)	525
7.1.1	The Matter of Problem	525
7.1.2	Axisymmetric Current Sheet Model and its Modification	527

7.1.3	Application to the Earth's Magnetosphere: The Ring Current and the Tail Current Systems	530
7.1.4	Contribution from the Magnetospheric Boundary Sources	533
7.1.5	Analysis of the Model's Parameters Depending on K_p . .	534
7.1.6	Model of Magnetic Field Distribution and Field-Line Configurations	537
7.1.7	Local Time-Dependence of the Average Inclination Angles	540
7.1.8	Distribution of Electric Current Density	540
7.1.9	The Model Field-Line Configurations for Several K_p Intervals	542
7.1.10	Summary of Main Results and Model Developing	545
7.2	Magnetospheric Configurations from a High-Resolution Data-Based Magnetic Field Model	546
7.2.1	The Matter of Problem	546
7.2.2	Modeling Equatorial Current System: Main Approach . .	547
7.2.3	Derivation of Vector Potentials	549
7.2.4	Magnetic Field Components	552
7.2.5	Spatial Variation of the Current Sheet Thickness	554
7.2.6	Approximations for the Shielding Field	554
7.2.7	Contribution from Field-Aligned Currents	555
7.2.8	Data Used for Magnetosphere Modeling	558
7.2.9	Regularization of Matrix Inversion Procedures	560
7.2.10	Data Weighting	561
7.2.11	Binning by K_p Index	563
7.2.12	Binning by the IMF B_z	564
7.2.13	Main and Recovery Storm Phases	565
7.2.14	Field-Aligned and Equatorial Currents	566
7.2.15	"Penetrating" Field Effect	568
7.2.16	Effects of the Dipole Tilt and IMF B_y on the Model Tail Current	569
7.2.17	Summary of Main Results	570
7.3	Storm-Time Configuration of the Inner Magnetosphere: Lyon–Fedder–Mobarry MHD Code, Tsyganenko Model, and GOES Observations	571
7.4	Magnetospheric Transmissivity of CR Accounting Variability of the Geomagnetic Field with Changing K_p and with Local Time (Within the Frame of the Tsyganenko-89 Model)	576
7.4.1	The Matter of Problem	576
7.4.2	The Calculation Method	577
7.4.3	Calculations of Transmissivity Functions	578
7.4.4	Asymptotic Directions for a High-Latitude Station	579
7.4.5	The Transmission Function at Middle Latitudes: Varying with IOPT	584

7.4.6	The Weighted Transmissivity Function	584
7.4.7	The Changing of the Transmissivity Function During Very Strong Geomagnetic Disturbance	584
7.4.8	Asymptotic Directions for a Middle-Latitude Station ...	587
7.4.9	Asymptotic Directions and Transmissivity Function for Low-Altitude Satellite Observations	589
7.4.10	Main Results and Discussion	590
7.5	Geomagnetic Cutoff Variations Observed by Tibet NM During the Maximum of Solar Activity: Checking Within the Frame of the Tsyganenko-89 Model	591
7.5.1	Tibet NM and Observation Data for Magnetic Storm Events	591
7.5.2	Analysis of Data and Comparison with the Tsyganenko-89 Model	593
7.6	Magnetospheric Effects in CR During the Magnetic Storm in November 2003	594
7.6.1	The Matter of Problem	594
7.6.2	Solar and Interplanetary Activity in November 2003 ...	597
7.6.3	Data and Method of Analysis	597
7.6.4	Uncorrected and Corrected for the Magnetospheric Effect CR Variations	599
7.6.5	Cutoff Rigidity Variations During the Magnetic Storm .	600
7.6.6	Correlation of the Obtained ΔR_{ci} with D_{st} Index	600
7.6.7	Latitudinal Dependences of Cutoff Rigidity Variations	603
7.6.8	Comparison of Cutoff Rigidity Variations Determined by CR Data and Derived from Magnetosphere Models by Trajectory Calculations	604
7.6.9	On the Consistency of the “Storm” Models with the Current Distribution Derived from Spacecraft Data	605
7.6.10	On the Specific Feature of the November 2003 Event and on the Radius of the Ring Current	607
7.6.11	On Possible Errors in Obtained Results	607
7.6.12	On the Sensitivity of NM to CR Magnetospheric Variation	608
7.6.13	Summary of Main Results	609
7.7	On Checking the Magnetosphere Models by Galactic CRs: The Great Magnetic Storm in November 2003	609
7.7.1	The Matter of Problem	609
7.7.2	Comparison ΔR_{sgs} Derived from CR Data and ΔR_{ef} Obtained by Trajectory Tracing Within in the Frame of the Ts03 Tsyganenko Model	611
7.7.3	Comparison of Absolute and Relative Maximum Decreases of CR Cutoff Rigidities	613

7.7.4	The Behavior of the Difference $\delta R_c = \Delta R_{sgs} - \Delta R_{ef}$	613
7.7.5	On the Correlations of ΔR_{sgs} and ΔR_{ef} with Parameters D_{st} , B_Z , B_Y , N_{SW} , and V_{SW}	613
7.7.6	On the Relations Between ΔR_{sgs} and ΔR_{ef} for Different CR Stations	615
7.7.7	Main Results and Conclusion	617
7.8	Checking of Magnetosphere Models by Solar CRs: GLE on January 20, 2005	617
7.8.1	The Matter of Problem	617
7.8.2	CR Data of NM on Mt. Jungfrauoch in Comparison with Other NM Data	617
7.8.3	Determining CR Cutoff Rigidity Variations During GLE within the Frame of Tsyganenko Models of Disturbed Magnetosphere; Correction of CR Data on Geomagnetic Variations	619
7.8.4	Determining Solar CR Angle Distribution and Energy Spectrum Time Variations, and Checking Self-Consistent CR Data with Tsyganenko's Magnetosphere Model	620
8	Galactic Cosmic Rays in Atmospheres and Magnetospheres of Other Planets	623
8.1	The Matter of Problem	623
8.2	The Properties of the Planetary Atmospheres	623
8.3	The CR Secondary Components, the Integral Generation Multiplicities, and the Coupling Functions in the Martian Atmosphere; Expected Latitude Magnetic Effect	626
8.4	The CR Secondary Components, the Integral Generation Multiplicities, and the Coupling Functions in the Atmospheres of Jupiter and Venus; Expected Latitude Magnetic Effect	629
	Conclusion and Problems	633
	References	637
	Appendix	683
	Subject Index	753
	Author Index	765

Frequently used Abbreviations and Notations

ACE	Advanced Composition Explorer satellite
a_n^m, b_n^m	Gauss coefficients for planetary magnetic field
CME	coronal mass ejection
CR	cosmic ray
Dst	disturbance storm time index
E	energy of CR particles
E_0	energy of primary CR particle
ESO	Israel–Italian Emilio Segre’ Observatory
FAC	field-aligned currents
FEP	Flare Energetic Particles
GLE	ground level event of solar CR increasing
H	altitude
h	atmospheric pressure
h_o	pressure on the level of observations
IC	ionization chamber, shielded by 10 cm Pb
ICME	interplanetary coronal mass ejections
ICRC	Israel Cosmic Ray Center (1992–2002)
ICR&SWC	Israel Cosmic Ray & Space Weather Center (from 2003)
ICRS	International Cosmic Ray Service (proposed in 1991)
IEF	interplanetary electric field
IGY	International Geophysical Year (July 1957–December 1958)
IMF	interplanetary magnetic field
IQSY	International Quiet Sun Year (1964–1965)
L	McIlwain parameter.
MC	magnetic cloud
m w.e.	meters of water equivalent
M_E	magnetic moment of the earth

$m_i(R, h)$	integral multiplicity: number of secondary CR particles of type i on level h from one primary CR particle with rigidity R on the top of atmosphere
m_o	rest mass of particle
MT	muon or meson telescope
$N(R_c, h)$ or $I(R_c, h)$	CR intensity
NM	neutron monitor or super-monitor
NM-64 or NM-IQSY	neutron super-monitor of IQSY type
NM-IGY	neutron monitor of IGY or Simpson's type
$R = pc/Ze$	particle rigidity
R_c	geomagnetic cutoff rigidity
r_E	radius of the earth
r_{dip}	the curve's radius of particle in the dipole magnetic field
r_o	the equatorial distance from the center of the geomagnetic line
SA	solar activity
SCR	solar cosmic rays
SEP	solar energetic particles
SNE	solar neutron events
SNT	solar neutron telescope
SW	Solar wind
SW	Space weather
$T(h)$	vertical air temperature distribution
$u = r_c/r_E$	(here r_c is the radius of the ring current in magnetosphere)
$W(R, h)$	coupling function
Z or θ	zenith angle
λ	latitude;
$\theta = \frac{\pi}{2} - \lambda$	the polar angle
θ_r	the polar angle of points of particles return
ϕ	the angle between magnetic field B and particle velocity v
φ	longitude, azimuth
$\rho = v_{\perp}/\omega_c = \gamma m_o c v \sin \phi / ZeB$	Larmor radius of particle in the magnetosphere
$\omega_c = ZeB/\gamma m_o c$	cyclotron frequency