Cosmic Rays in Magnetospheres of the Earth and other Planets
Cosmic Rays in Magnetospheres of the Earth and other Planets

Lev Dorman

Springer
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)
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. Lemaitre 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 ×15° 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 Swedish–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. Villoresi. 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.

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Qazrin, Moscow, Princeton

Lev I. Dorman
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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.

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