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ScienceDirect
Advances in Space Research 44 (2009) 1107–1123
ADVANCES IN SPACE RESEARCH (a COSPAR publication)
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Fifty years of progress in geomagnetic cutoff rigidity determinations

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Received 16 May 2008; received in revised form 24 June 2009; accepted 3 July 2009

Abstract

This paper is a review of the progress made in geomagnetic cutoff rigidity calculations over the past 50 years. Determinations of cosmic ray trajectories, and hence cutoff rigidities, using digital computers began in 1956 and progressed slowly until 1962 when McCracken developed an efficient computer program to determine cosmic ray trajectories in a high degree simulation of the geomagnetic field. The application of this cosmic ray trajectory technique was limited by the available computer power. As computers became faster it was possible to determine vertical cutoff rigidity values for cosmic ray stations and coarse world grids; however, the computational effort required was formidable for the computers of the 1960s. Since most cosmic ray experiments were conducted on the surface of the Earth, the vertical cutoff rigidity was adopted as a standard reference value. The effective cutoff value derived from trajectory calculations appeared to be adequate for ordering cosmic ray data from latitude surveys. As the geomagnetic field evolution became more apparent, it was found necessary to update the world grid of cutoff rigidity values using more accurate descriptions of the geomagnetic field. In the 1970s and 1980s it became possible to do experimental verification of the accuracy of these cosmic ray cutoff determinations and also to design experiments based on these cutoff rigidity calculations. The extensive trajectory calculations done in conjunction with the HEAO-3 satellite and a comparison between these experimental measurements and the trajectory calculations verified the Störmer theory prediction regarding angular cutoff variations and also confirmed that the structure of the first order penumbra is very stable and could be used for isotope separation. Contemporary work in improving cutoff rigidities seems to be concentrating on utilizing improved magnetospheric models in an effort to determine more accurate geomagnetic cutoff values. When using geomagnetic cutoff rigidity values to predict the cosmic radiation access to spacecraft for a satisfactory computation of the radiation dose, both the particle transmission though the cosmic ray penumbra and angular cutoffs must be considered.
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Keywords: Geomagnetic cutoff rigidity; Cosmic rays; Cosmic ray trajectory-tracing; Geomagnetic field; Cosmic ray radiation dose; Cutoff rigidity calculation history

1. Introduction

The accurate calculation of particle trajectories in the Earth's magnetic field has been a long-term goal for cosmic ray researchers. The initial trajectory-tracing work of Störmer was accomplished by hand calculations of particle motion in a dipole field (Störmer, 1930, 1950). Lemaitre and Vallarta (1936a,b) utilized a machine now called an analogue computer to calculate families of trajectories and define the fundamental concepts of cosmic ray cutoff rigidities. The use of digital computers for the calculation of cosmic ray trajectories began in 1956 (Jory, 1956; Lust, 1957; Kasper, 1959) and progressed slowly until 1962 when McCracken developed an efficient computer program to determine cosmic ray trajectories in a high degree simulation of the geomagnetic field (McCracken et al., 1962). Fig. 1 is an illustration of the classic cosmic ray trajectory. Fig. 2 illustrates the type of complex trajectory that occurs near the cutoff rigidity of a cosmic ray station.

2. Initial cutoff rigidity determinations

In the 1960s the approximation method of Quenby and Webber (1959) to estimate the cutoff rigidity of specific

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0273-1177/$36.00 Published by Elsevier Ltd. on behalf of COSPAR.
doi:10.1016/j.asr.2009.07.005

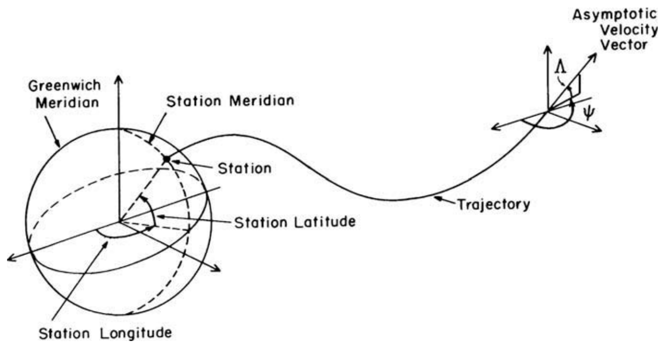

Fig. 1. The classic illustration of an allowed cosmic ray trajectory and the asymptotic directions of approach. These parameters are used to study spatial anisotropies and relativistic solar proton events (i.e. ground-level enhancements). From McCracken et al. (1962).

locations was used by Cogger (1960) to determine a cutoff value of 1.74 GV for the neutron monitor at Port-aux-Francais, Kerguelen Islands. In an analysis of the November 12 and 15, 1960 relativistic solar cosmic ray event, Freon and McCracken (1962) noted that the enhancements observed by the Port-aux-Francais monitor were consistent with the enhancements observed by other stations with a much lower cutoff rigidity. This suggested that the value of 1.74 GV for Port-aux-Francais was too high.

Using his newly developed trajectory-tracing method and the computer at the Massachusetts Institute of Technology, McCracken determined that the vertical cutoff rigidity at Port-aux-Francais was approximately 1.30 GV. When this value was used in the analysis of the November 1960 events, the increases recorded by the Port-aux-Francais neutron monitor were consistent with the observations of stations having similar cutoff rigidities. Freon and McCracken (1962) concluded that the simplifying approximations made by Quenby and Webber (1959) were not valid at least for Port-aux-Francais.

In the course of this work it was also noted that the computations were rather time-consuming for rigidities in the vicinity of 1.0 GV with each trajectory requiring about four minutes on an IBM 704 computer, provided that the rigidity was not too close to the actual cutoff rigidity. Near cutoff the computation time would be many times greater. Freon and McCracken also recognized that the cosmic ray penumbra (Störmer, 1950) would require extensive computer time for mid-latitude locations.

As computers became faster it was possible to determine vertical cutoff rigidity values for specific cosmic ray stations; however, the computational effort required was formidable for the computers of the 1960s (see McCracken, 2008, for reminiscences of this period). For example, the vertical cutoff rigidity determinations for cosmic ray stations included in the IQSY Instruction Manual No. 10 (1965) that contained cosmic ray trajectory-derived cutoff rigidities for the IQSY cosmic ray stations, with selected sets of asymptotic directions and variational coefficients required about three months of background computations on the then state-of-the-art US Air Force Space Track Computer.

With the ability to trace cosmic ray trajectories in a mathematical model of the geomagnetic field utilizing the then-available high speed computers, the next logical step was to perform a series of these calculations to determine the cutoff rigidity for several locations on the Earth. Over the next three years, Shea et al. (1965) proceeded to develop a consistent method to calculate the vertical cutoff rigidity for approximately 150 geographical positions including the locations of about 100 cosmic ray detectors.

Starting at rigidities high above the anticipated cutoff values, Shea et al. (1965) calculated cosmic ray trajectories

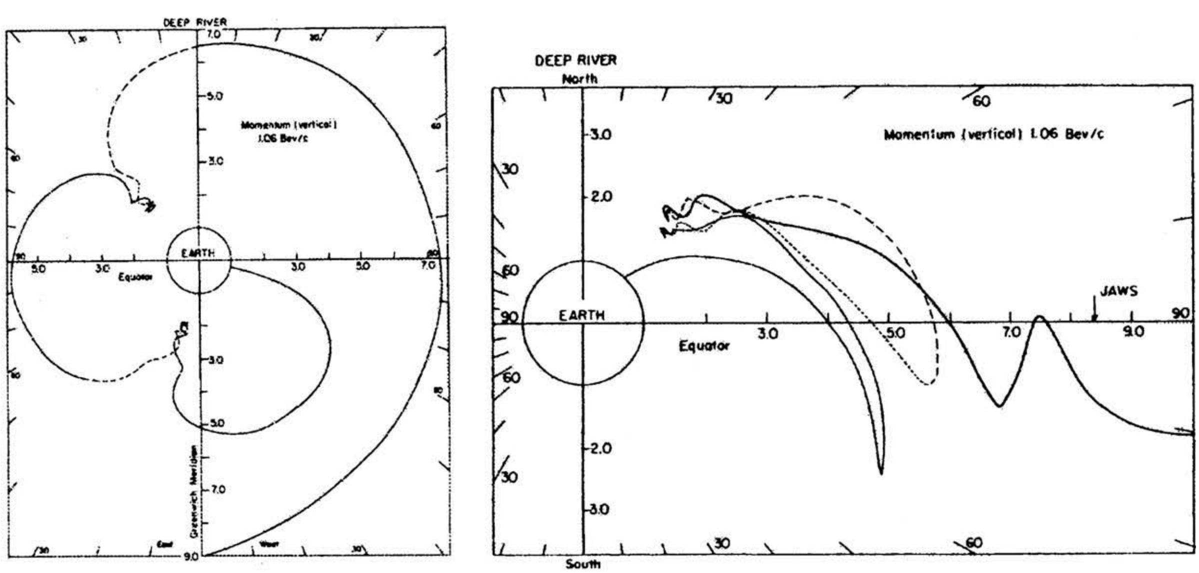

Fig. 2. An illustration of the complexity of the trajectory of a near-cutoff cosmic ray that would be vertically incident at Deep River, Canada. Left, the trajectory projection in the *R*-Theta plane. Right, the same trajectory projected in the *R*-Phi plane. *R* is the distance from the Earth's center; Theta is the geographic latitude, and Phi is the geographic longitude. From McCracken et al. (1962).