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Computer simulation of cosmic ray trajectories in near earth space

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Abstract. The dynamics of the cosmic ray ions of energy 10-100 MeV/N in and around the terrestrial magnetic field is studied using the method of trajectory tracing. The trajectory of a cosmic ray particle is back traced from the point of observation in the simulated magnetic field adopted by IGRF. The magnetic field used for this purpose is calculated from the magnetic potential described in the form of spherical harmonic multipole expansion of order 10 and degree 10. This represents only the static magnetic field due to the sources internal to the earth. The purpose of the study is to investigate (1) the conditions of transmission of cosmic ray particles into the geomagnetic field and the statistical characteristics of the distribution of such ions near the earth's surface; (2) the sensitivity of the parameters involved in the trajectory computation, such as the ionization state, energy, arrival location, arrival direction etc.

Key words : cosmic ray ions—dynamics—geomagnetic field

1. Introduction

For a detailed knowledge on cosmic ray origin and propagation in the low energy region, it has become essential to study the ionization states and charge composition of these particles. The Anuradha experiment was carried out mainly to achieve this objective by measuring the charge state of atomic ions of carbon and above. For this purpose, it becomes necessary to study the motion of these particles in the geomagnetic field which, in turn, depends on their rigidity (momentum/charge). The rigidity solely decides the trajectory of such particles in the deterministic fashion in the magnetosphere, irrespective of its species, energy, charge states etc. We studied the trajectories of individual cosmic ray particles in 10-100 MeV/N energy range in the earth's magnetosphere keeping the following points in mind.

1. To understand the behaviour and to develop a feel for the dynamics of cosmic ray ions in and around the geomagnetic field.
2. To determine the relative importance of various parameters, such as energy, charge state, arrival location, arrival direction etc.
3. To demonstrate the types of events that are taking place in and around the magnetosphere.

4. To show that the method, indeed, can be used to determine the ionization states of atomic ions from the cutoff rigidity at a location on earth.
5. To determine the distribution of such particles as they arrive at the top of the atmosphere.

For the purpose of this study, we confined ourselves in the rigidity range of 0.5-10 GV; because particles with rigidities outside this range show very simple behaviour. The cosmic ray particles with rigidities less than 0.5 GV get deflected away by the magnetosphere or arrive at the poles only. Particles with rigidities higher than 10 GV penetrate almost freely except very close to the geomagnetic equator. In the first part of the study, the trajectories are computed in backward direction from the point of detection at the top of the atmosphere in the simulated magnetic field. If for a given rigidity, the trajectory of such a simulation leads to the outside of the magnetosphere, above 25 earth radii, the trajectory is said to be allowed; i.e. a real particle with the given rigidity could come along the path traced to arrive at the point of detection. Whereas if the trajectory is closed (bound), i.e. the simulation leads back to the earth, then it is not possible for a real particle to arrive at the location at the given angle of incidence. For the second part of the study, to determine the distribution of cosmic rays arriving on the earth, the trajectories are computed in forward direction assuming an isotropic distribution of such particles in the interplanetary medium moving uniformally in all directions. In this case, the starting point of trajectory computation is about 10-12 earth radii away from the centre of the earth.

These trajectories were displayed on a high speed graphics workstation using the techniques of animation and shading. Enumerable number of features, such as, the existence of critical zones in rigidity space, the effect of umbra and penumbra in rigidity space, the magnetic mirroring, could easily be seen. The critical zone in rigidity space is a range of rigidity values for which the trajectory becomes extremely complex and unstable. The same method is also used to study the distribution of cosmic rays particles on earth arriving from interplanetary space. In an simulated environment, the cosmic rays were randomly generated at some distance (10 earth radii in the present study) uniformly spaced around the earth moving in uniformly distributed directions to follow the trajectories. The spatial distribution and the distribution of arrival directions were determined for all those that arrived at the earth.

2. Procedure

Unlike dipole field model, there does not exist a closed form formula for the cutoff rigidity in this model; instead we trace the trajectories of the individual particles by integrating the following differential equation.

$$\ddot{\mathbf{R}} = q(\dot{\mathbf{R}} \times \mathbf{B}) \qquad \dots (1)$$

This multipole expansion model is a fairly satisfactory simulation of the true Geomagnetic field and the best description so far. For our purposes we adopted and modified a computer code in FORTRAN provided by Shea and Smart. A fourth order Runge-Kutta method is used to solve the second order differential equation of the form given in equation 1. In this method the initial position and velocity associated with a rigidity provide the initial conditions in the integration and the trajectory is calculated in small steps in time.

3. Results

For a given location on earth and a given angle of incidence, there exists a lower cutoff of rigidity, *RL*, such that a particle with the rigidity lower than that can never arrive. Similarly, there exists an upper cutoff of rigidity, *RU*, above which all rigidities are allowed. In the intermediate range, the trajectories are very complex and they exhibit penumbral structure of bands of rigidity ranges of allowed and forbidden trajectories. The effective cutoff rigidity, *RC*, in the penumbral structure, is computed in the following manner.

$$RC = RU - \sum_{RL}^{RU} \Delta R_{\text{allowed}} \qquad \dots (2)$$

The penumbra is caused by the presence of the solid earth; some of the trajectories with intermediate rigidities hit the atmosphere. If only the magnetosphere existed without the solid mass of the earth, all particles with rigidities higher than the lower cutoff would have been allowed, giving a sharp cutoff at *RL*. Numerical computations of the trajectories have been the only method which show the penumbral structure in the rigidity space. The rigidity range between the two limits is referred to as Critical Zone.

The results of the simulation of individual trajectories are shown by a series of figures 1 to 5.

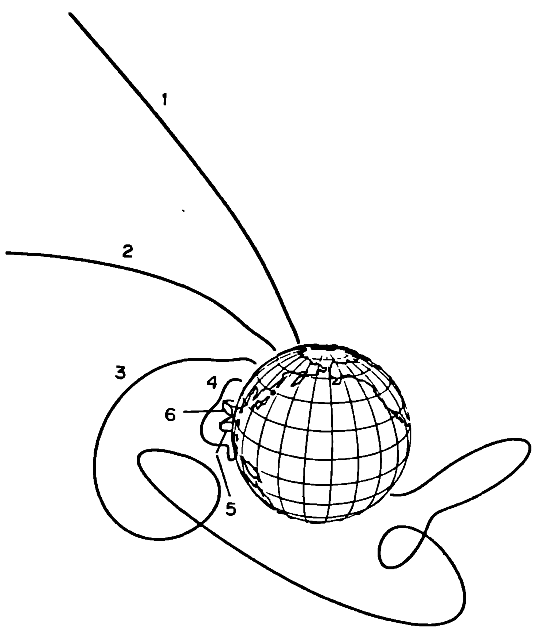

Figure 1. A constant set of values is assigned to a set of parameters, and trajectory computation started from 6 different latitudes on the same meridian. The trajectories progressed in the backward direction while the low latitude ones soon terminated giving rise to bound trajectories, indicating that the real particle cannot penetrate the earth's magnetic field. The two high latitude events show open trajectories, indicating the possible paths for cosmic ray entry, while the one starting from an intermediate latitude show the complex behaviour.

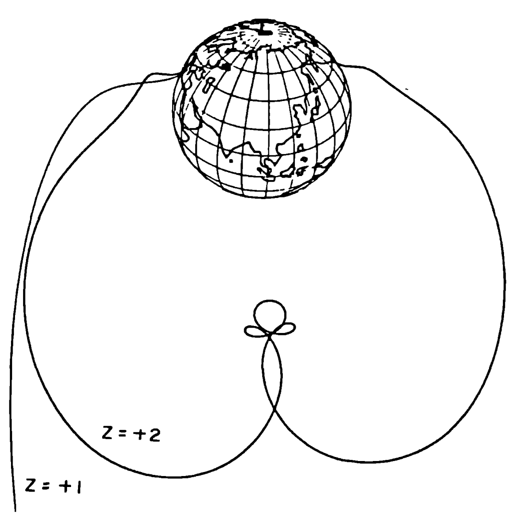

Figure 2. Two events, having the same values for all parameters except the charge states +1 and +2 respectively. The one with charge state +1, having high rigidity produces an open trajectory whereas the other one with charge state +2 could not produce an open trajectory. This establishes the particle detected as singly ionized.

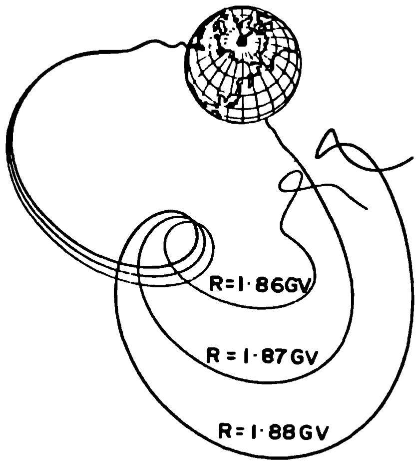

Figure 3. An event with three different values of rigidities 1.86, 1.87, 1.88 GV respectively. One observes that the one with the intermediate rigidity, 1.87 GV, strikes the earth whereas the other two produce open trajectories, indicating the penumbral structure in rigidity space.

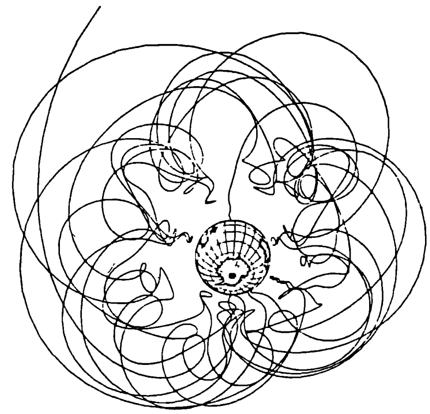

Figure 4. A complex trajectory in the critical zone of rigidity exhibits magnetic mirroring several times due to magnetic bottle neck.

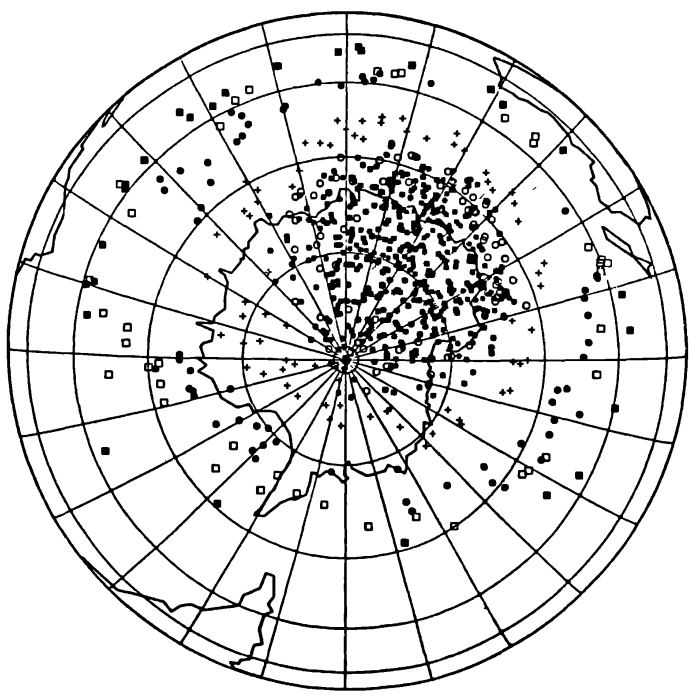

Figure 5. A view from the polar region of the cosmic ray clustering. The ⊕ indicates the geographic north pole. The bands of points in different symbols show the cosmic ray distribution around the north pole; note the separation of magnetic pole from the geographic pole. These are produced by the simulated events traced from the interplanetary medium to the surface of the earth. The figure clearly shows non overlapping annuli of points in different symbols. These separate rings are produced by the set of events which were approaching the earth in different angular bins. For example, (1) the nearest points to the geomagnetic pole (forming a circular patch) in '*' are produced by those events which were heading towards the earth to within 10° to the line joining the starting point of simulation and the earth; (2) an annulus formed by open circles is produced by the events which started off above 10° with the same solid angle and so on.

4. Conclusions

The explicit and accurate simulation of the geomagnetic field and the behaviour of 10 to 100 MeV/*n* particles in this field reveals several interesting and important results. The features like the umbra, penumbra, the latitude, energy as well as the charge state effects on particle propagation in the geomagnetic field can be clearly understood. The impinging of particles from large distances onto the earth reveal several hitherto unsuspected features of particle propagation in the geomagnetic field which require detailed investigations.