Solar energetic particles in the Earth magnetosphere: 
kinematic modeling of the “non-shock” penetration

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Abstract. Penetration of solar energetic particles into the Earth’s magnetosphere is quantitatively studied with a simple kinematic model. The goal is to assess, for the first time, how does effectiveness of the penetration depend on such geometry factors as: distance of the magnetopause (MP) from the Earth; shape of MP; angle at which solar energetic particle crosses MP; location of the crossing point; type of the particle motion in the magnetosphere. To get off excessive details, the model deliberately operates with just equatorial section of the static dipolar magnetic field confined with asymmetric boundary – MP. Several rather obvious facts are illustrated: finite orbits of longitudinal drift reside only inside the circle of the Störmer-unit-length radius; deepest penetration of a particle occurs if the particle crosses MP at the point closest to the Earth and with velocity-vector oriented along the particle’s longitudinal drift inside MP (westward for protons); etc. The model’s software allows the inquirer to vary geometry of MP, the type, energy and direction of flight of the energetic particle(s), the location(s), aperture and orientation(s) of a virtual sensor, then to run the model and obtain the reference particle distributions either global (for entire magnetosphere) or for specified locations, all along the time, energy and flux-orientation axes. Static and animated plots can be easily produced. The model provides a toolkit allowing one to evaluate and illustrate the process of particle penetration into the magnetosphere under various conditions in space. It may be used for the configuring of the satellite particle sensors; its results may be compared with the observations for to assess how strongly the real magnetosphere differs from its simplified form; it may be used in education.

1. Introduction

Typically, the cosmic-ray scientists deal with particles that arrive from space and interact with the atmosphere and ultimately become detectible at the ground level. In contrast, this paper addresses somewhat different sort of cosmic rays – the solar cosmic rays (also known as solar energetic particles – SEP) whose lower energy lets them pass only through the outer layers of the magnetosphere and not get too close to the Earth. Those particles are detectable on satellites, they impose radiation hazard to both satellites and crews of manned space missions. Due to relatively low energy, SEP may be sensitive to structural features of the medium they flew through and thus they may be considered as candidates to be the space tracers.

Most studies of the particle penetration into the Earth’s magnetosphere are historically based upon the analytic theory by Carl Störmer (e.g. in [1]) and also on the method of time-reversal tracing of the particle motion from the point of observation; the method was used, e.g., in [2] and in the software package MAGNETOCOSMICS [3]. These both well fit the needs of the cosmic ray science but neither the needs of the satellite safety nor of the physics of the magnetosphere. The difference is in that, in the later cases, the region of interest is not a single on-ground point but the entire magnetosphere in which a spatial distribution of SEP and temporal variations of this distribution have to be determined as a function of the external (relative to the magnetosphere, that is, properties of the flux of SEP in the interplanetary, i.e. IP, space) and internal (properties of the magnetosphere) conditions. Of special interest is also a transfer of SEP to the state of trapped particles – those living in the magnetosphere for a long time.

As is shown below, penetration of SEP into the magnetosphere (MS) strongly depends on geometry of asymmetric boundary of MS – the magnetopause (MP), and on geometry of the contact of the incident flux with MP (location and angle of the incidence). Quantification and illustration of these rather obvious yet scarcely elucidated in literature effects is a goal of the study [4, 5] briefly reported herein.
2. The model
To attain the goal, a simplified kinematic model has been developed which holds only major relevant factors of the SEP-MS interaction and omits many others. In particular: (1) geomagnetic field is assumed to be dipolar yet confined with a realistically asymmetric boundary – MP; (2) only motion of a particle in the plane of geomagnetic equator is considered; (3) for each modeled case, magnetic field and the shape of MP are supposed static, so far. As the quantitative parameters of the particle penetration into MS, the following are taken: maximal depth of penetration (i.e. minimal radial distance to the Earth reached by the particle, $r_{\text{Min}}$), and period of longitudinal drift of the particle $t_{\text{Orbit}}$. Protons are considered as a sole component of SEP; their kinetic energy is within $1\ \text{MeV} – 1\ \text{GeV}$; equation of the particle motion is taken in relativistic form. As MP may be chosen a circular, elliptical or parabolic curve or an empirical parameterization by [6]. The software code (written in IDL and called SPIM2D) allows the user to choose the shape of MP and its distance from the Earth, and also the number, direction and energy of the incident particles, and then to start the particle tracing. The Runge-Kutt integrator is used to obtain the trajectories. Each run results in: the tracing’s plots; the obtained $r_{\text{Min}}$ and $t_{\text{Orbit}}$; optional plots of the SEP distributions in MS (spatial, energy and angular) either global or observed by a variously oriented sensor placed at the specified locations. The trajectories’ plots and distributions may be also saved as static and/or animated GIF-files which may be played back later so that to demonstrate the stages of the SEP propagation with realistic (by default) speed of the process.

Dipolar form of geomagnetospheric field, mentioned above in (1) is a widely used approximation capable to approximate major features of the most powerful central part of the real field. Shape of MP appears from the standing of the magnetic pressure inside MS against locally normal component of the ram pressure of the solar wind. Term (2) reduces the problem to the two-dimensional (2D) form, which yields not too much to a loss of generality and is a frequently used simplification. The third condition, (3), disallows for the model to interpret cases of rapid and/or strong deformation of MS by IP-shocks followed by radial transportation and changes of energy of SEP in MS.

3. Penetration depth as a function of the entry point and incidence angle
Figure 1 illustrates differences in filling of MS with SEP arrived from different directions. Figures 2a and 2b show the role of the Störmer unit length as a separatrix of the (quasi-)trapped and loose types of motion of a particle in MS (see the caption); Figures 2c and 2d summarize the results on several runs and represent $r_{\text{Min}}$ and $t_{\text{Orbit}}$ as a function of both radial distance and incidence angle of a particle (several energies are tested) entering the MS. Conclusions for this part of the study are as follows: (1) the deepest penetration occurs if the particle enters MS at the sub-solar dip of MP with a
westward velocity vector nearly tangent to MP; (2) the pre-noon crossing of MP may allow a particle to be trapped (at least it can be quasi-trapped for an almost complete orbit of longitudinal drift through the night sector) while the afternoon crossing — may not, although the exact separatrix between these zones shifts to the afternoon for the higher-energy particles; (3) the (quasi-) trapping is allowed only if the orbit of the particle’s gyro-rotation lies inside the Earth-centered circle whose radius is the Störmer unit length (which length depends on the particle’s energy).

4. Global distributions
Multiple-particle runs of the model provide launches of ensembles of SEP at various angles from the variously situated MP, under various other conditions; the resulting distributions of SEP inside MS are obtained globally and for specified observation points and sensor orientations. The distributions are responsive to the conditions some of which are being routinely measured (the IP magnetic field and the ram pressure of solar wind), some can be measured (pitch-angle distribution of SEP outside MS) and some other are difficult for observation (geometry of MP); thus, the combining of the model and the parameters measured inside and outside MS must help in obtaining the information about MP.

Figure 3 shows the example plots of three multi-energy model runs with activated virtual sensors; the sensors are located at 12 points of the geosynchronous orbit with 18 orientation angles each; SEP fluxes in the first two runs are monodirectional and are isotropic in the last run; the shown data were collected for the first five seconds after the particle launch from MP. Distinguishability of the spectra in the stacks gives a hope to make use of them for to get information on MP and the incident SEP.

5. Conclusions
The model may be helpful in the configuring of instrumentation for the satellite observations of SEP inside MS. Although periods of high geomagnetic activity are principally not covered by the pre-
sented static model, and in some such cases observations strongly disagree with the model, the comparison of the reference model predictions and the actually measured SEP penetration may provide a rough assessment on how far the real disturbed geomagnetic field has gone from the dipolar form. Since SEP often arrive to the Earth prior to the beginning of a geomagnetic disturbance or in absence of that, the just mentioned assessment may be made also for the rather quiet magnetic conditions. Generally, the model provides the means for the visualization and evaluation of the basic effects of the particle penetration into the magnetosphere, which may be applied in science and education.

Figure 3. Top: After three model runs, MS if filled with the particle trajectories whose color codes energy of a proton, from green – 10 MeV to red – 1GeV; V-arrows indicate directions of the launches. Bottom: stacks of energy-angular distributions obtained at twelve points evenly dispersed along geosynchronous orbit (as indicated in the LT columns) with a multi-directed sensor; the stacks correspond to the respective trajectory plots above; each layer of a stack is a spectrum with X-axis representing the orientation of the sensor relative to the Earth, Y-axis – the particle’s energy, color – normalized number of collected particles.

References
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