Dynamics of Solar Energetic Particles in Geospace

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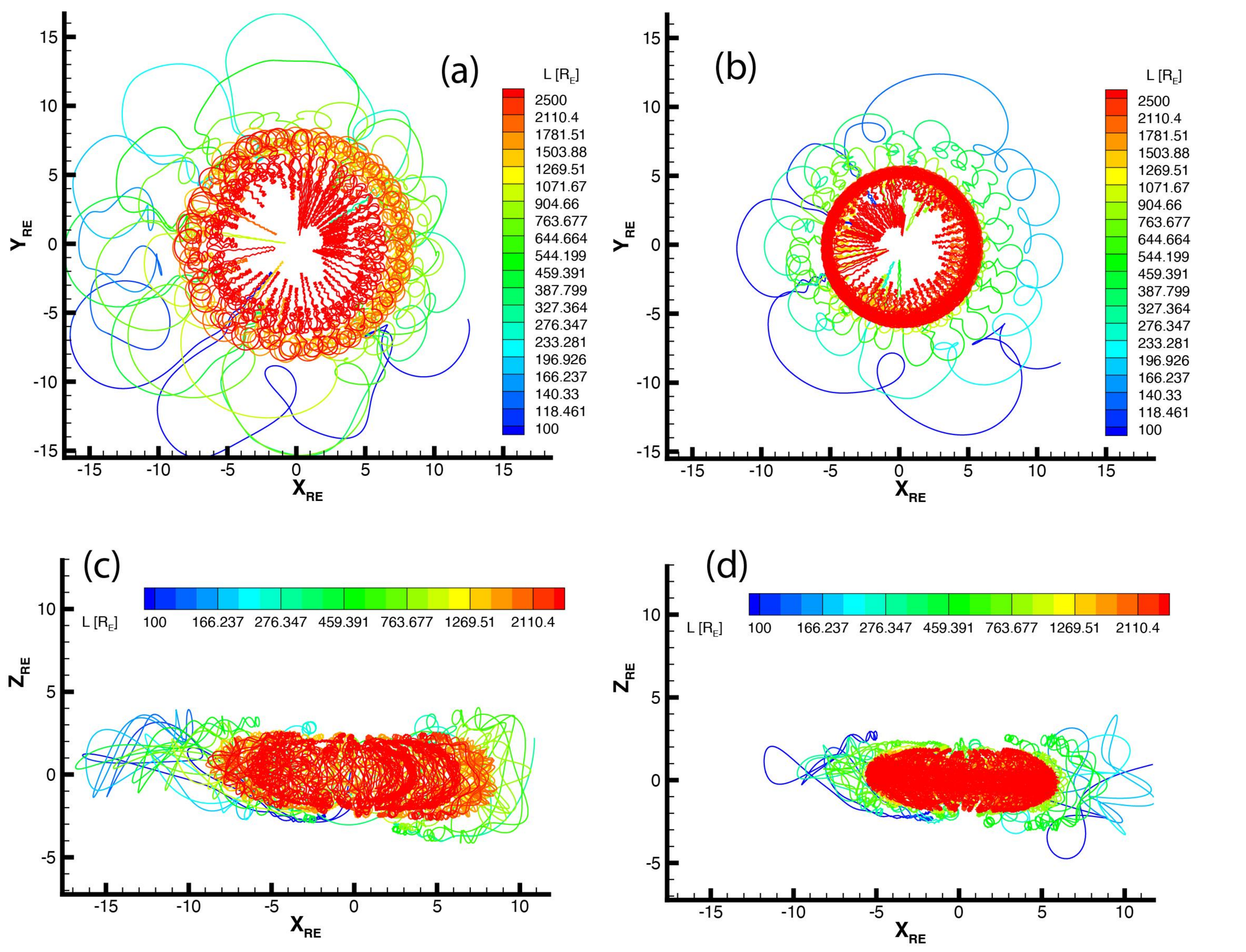
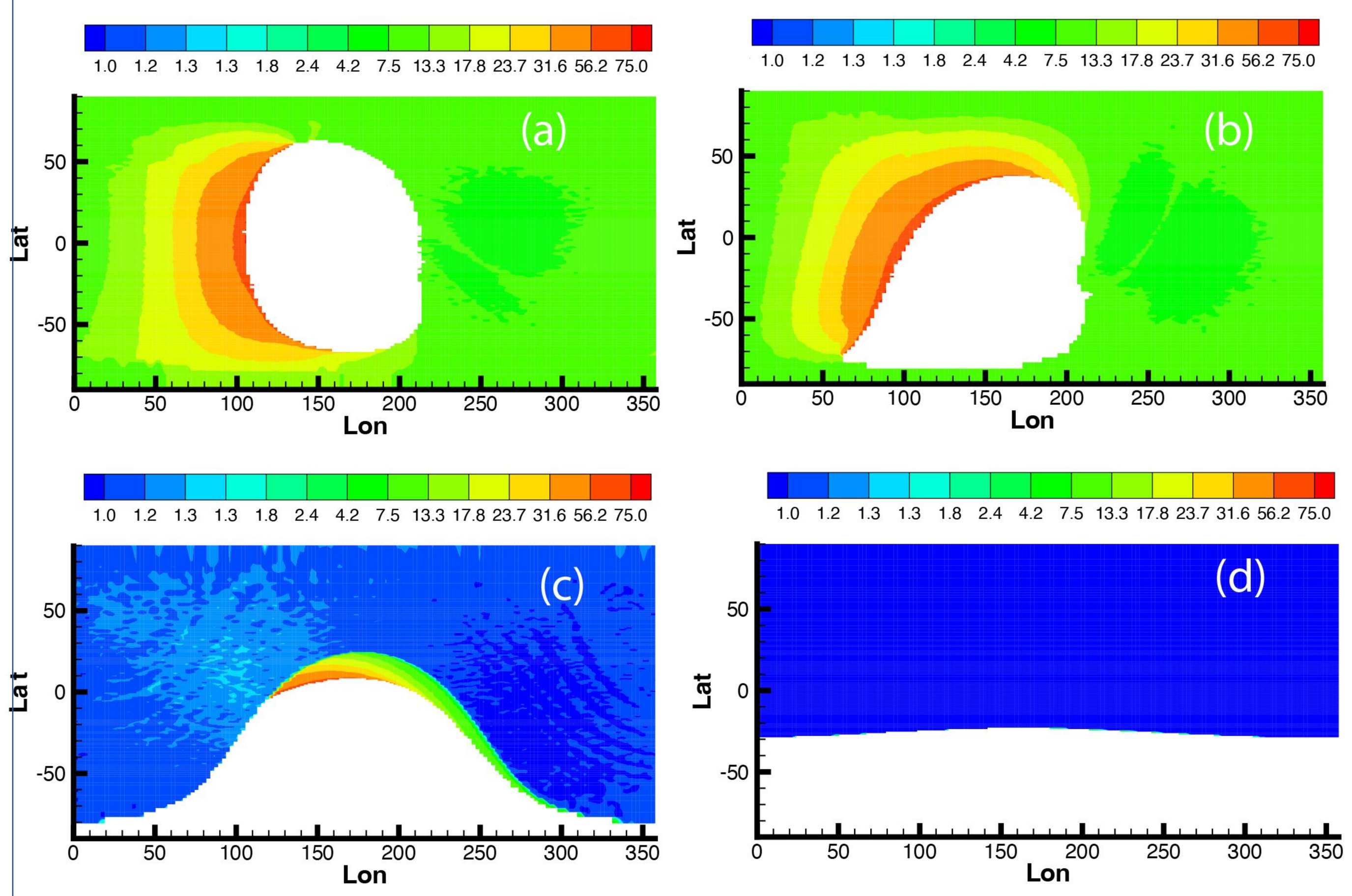
Abstract

Penetrating radiation by energetic particles significantly affects human technology in the altitude range above that used by commercial aviation in the troposphere. In space, exposure to energetic particles often leads to malfunctions and unexpected failures of electronics onboard manned and unmanned spacecraft and poses a severe health risk for astronauts.
The work presented in the paper is focused on characterizing the SEP population in geospace in the altitude range starting from that of LEO through MEO and GEO, and up to the magnetopause accounting for the realistic geomagnetic field. The dynamics of SEPs are studied during quiet and geomagnetically active times using Monte Carlo simulations.
The paper discusses the variability of the SEP population in geospace in response to geomagnetic activity. Manifestation of the former is temporal trapping of SEPs in geospace and suppression of the rigidity cutoff during geomagnetic storms.



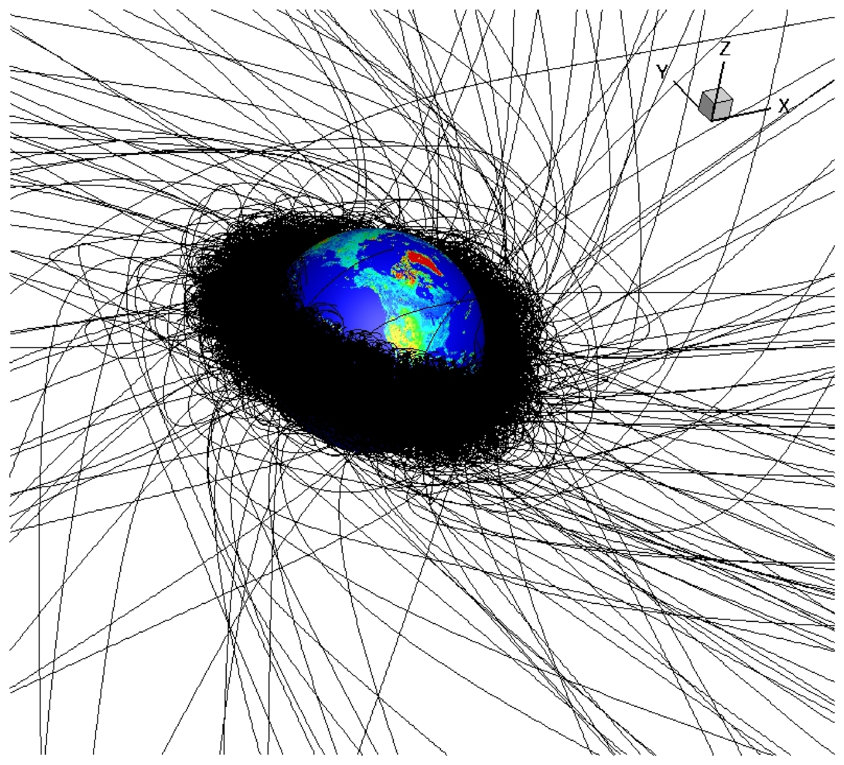
The figure illustrates trajectories of the solar protons captured during a magnetospheric storm. Panels a and c shows a trajectory of a single solar wind proton projected onto XY and XZ planes. The trajectory of another solar wind proton is in panels b and c. The figures show parts of the particle trajectories when the particles are closer than L=10 The color is the trajectory distance of those protons in the geospace. One can see that the protons "diffuse" to the $L\sim2$, which is caused by variation of the geomagnetic field during a magnetospheric storm. One can see that the total trajectory distance of a solar wind proton before it is captured at L=2 is about 2×10^3 R_E.



The map is calculated for an altitude of 500 km. The cutoff is calculated at the location in the x-z plane of the SM coordinate frame when the vector connecting the point, and the center of the frame of reference is 0º panel a, 20º panel b, 60º panel c, and 90º panel d. That corresponds to locations x=(6.87×10^3 km, 0, 0), x=5.95×10^3 km, 0, 3.45×10^3 km), x=(3.45×10^3 km, 0, 5.95×10^3 km), and x=(0, 0, 6.87×10^3 km), respectively.
The figure illustrates the effect of the Earth's shadowing and the effect of the east-west asymmetry (panels a,b,c).

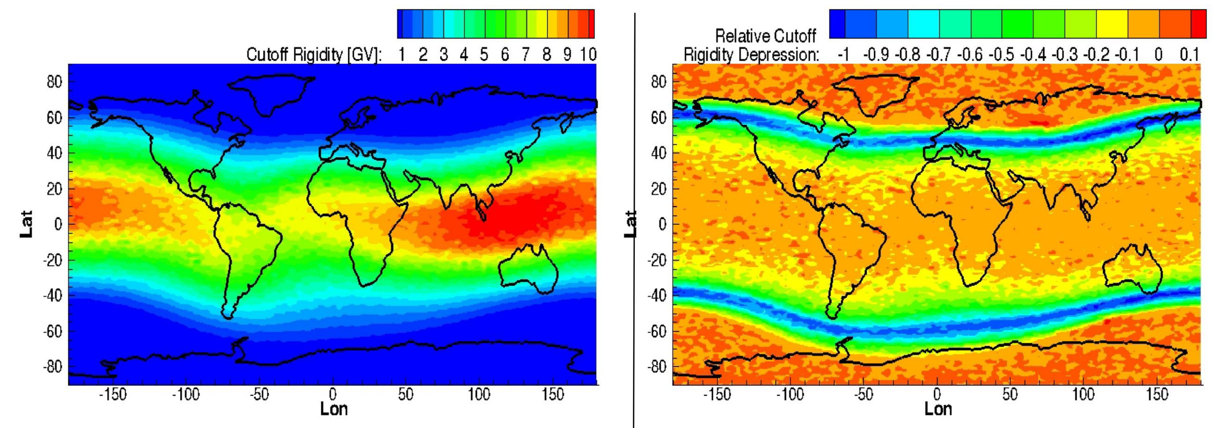
Tracing trajectories of energetic particles in geospace

Forward modeling of the energetic particles is computationally expensive and, therefore, inefficient when energetic particle flux, energy spectrum, or cutoff rigidity are needed to be determined only in a limited set of locations. In that case, a backward tracing of the energetic particles starting from the points of interest computationally is more preferable. Example of such calculation conducted with AMPS is presented below



Rigidity cutoff map calculation

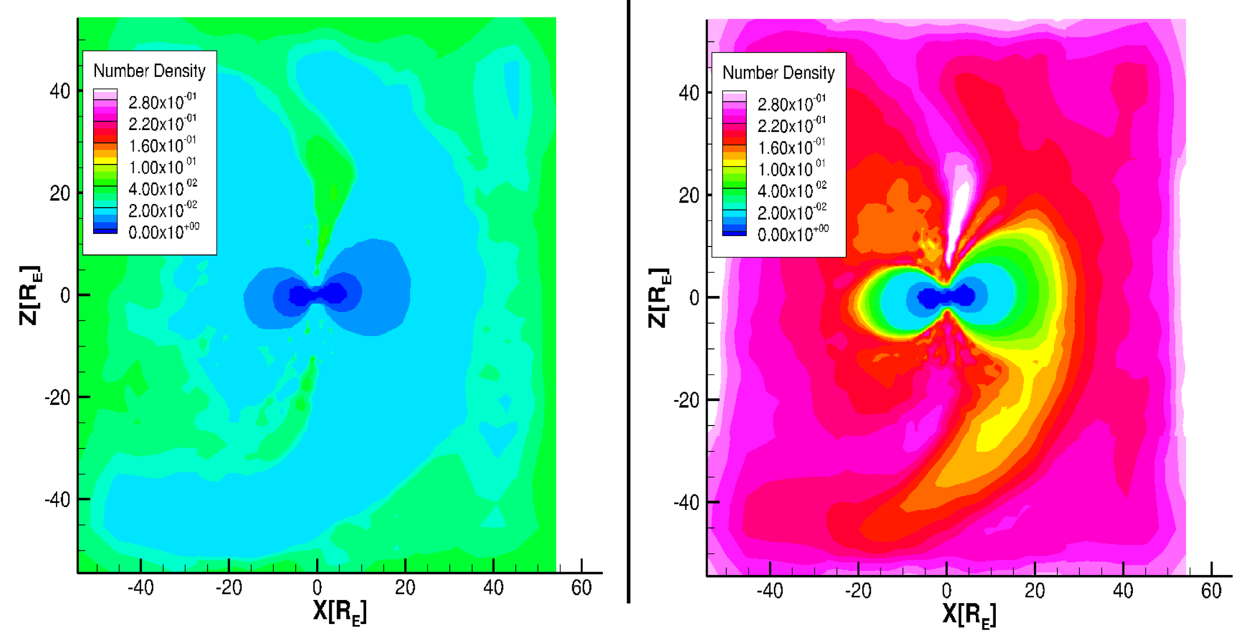
The calculation was performed for conditions of the geomagnetic storm on March 17, 2015. In general, rigidity cutoff suppression is more significant in the mid-latitude region.



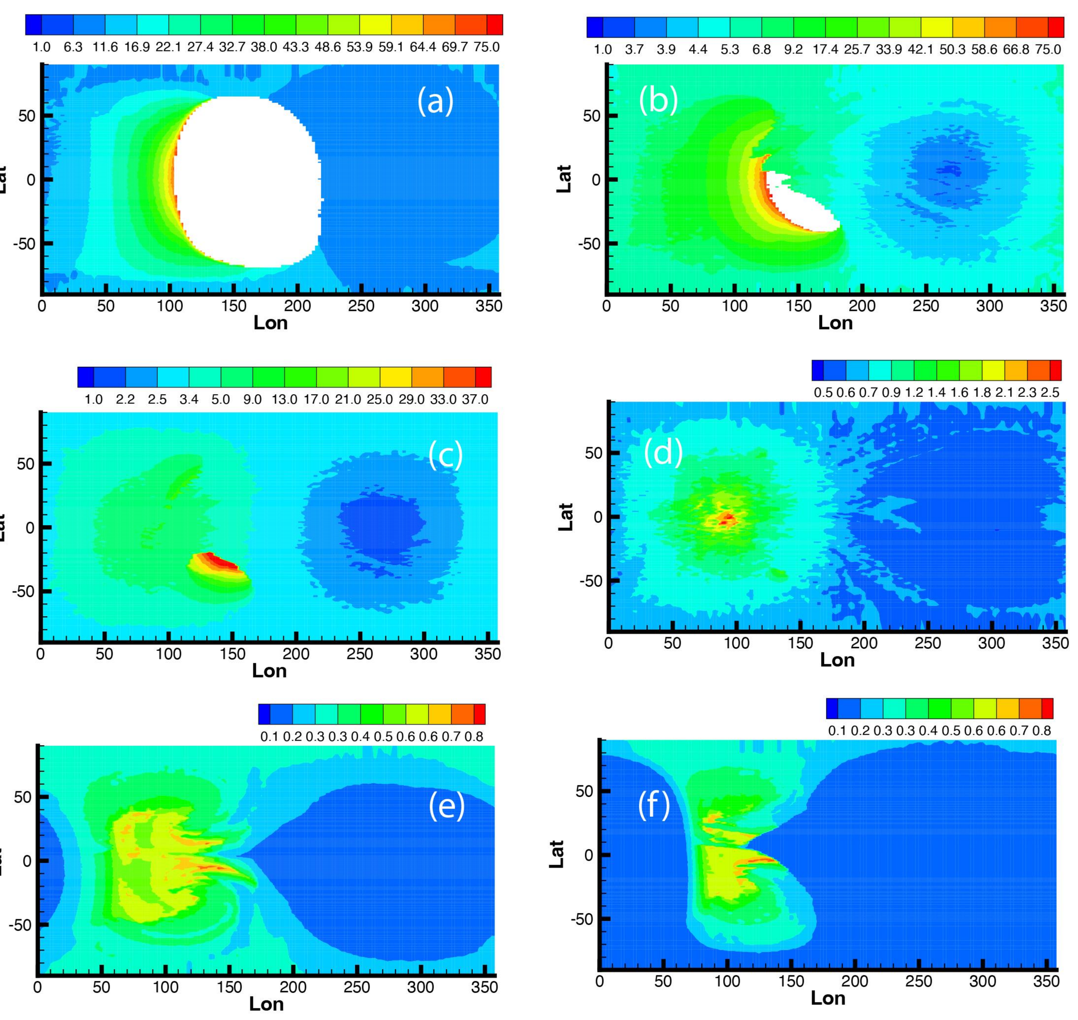
Population of SEPs in geospace

Event: 2017-09-09 - 2017-09-12

Density of the energetic particles increased by an order of magnitude



Before the event   Main phase of the event



The figure illustrates the directional dependence of the calculated rigidity cutoff. The rigidity cutoff is calculated at x=(6.771×10^3 km,0,0), x=(9.55×10^3 km,0,0), x=(1.27×10^4 km,0,0), x=(2.55×10^4 km,0,0), x=(5.1×10^4 km,0,0), and x=(5.65x104 km,0,0).

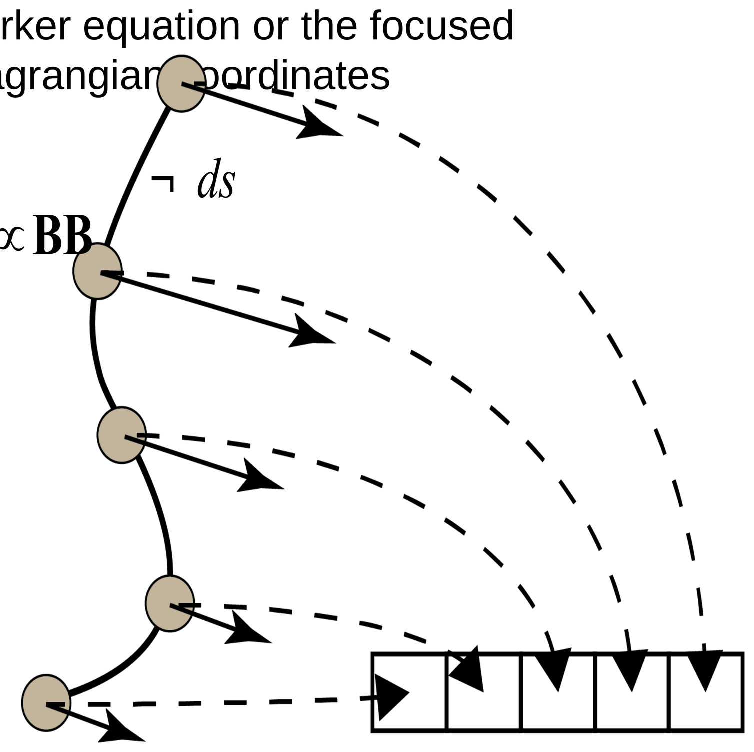
Determining spectrum of SEPs entering the geospce

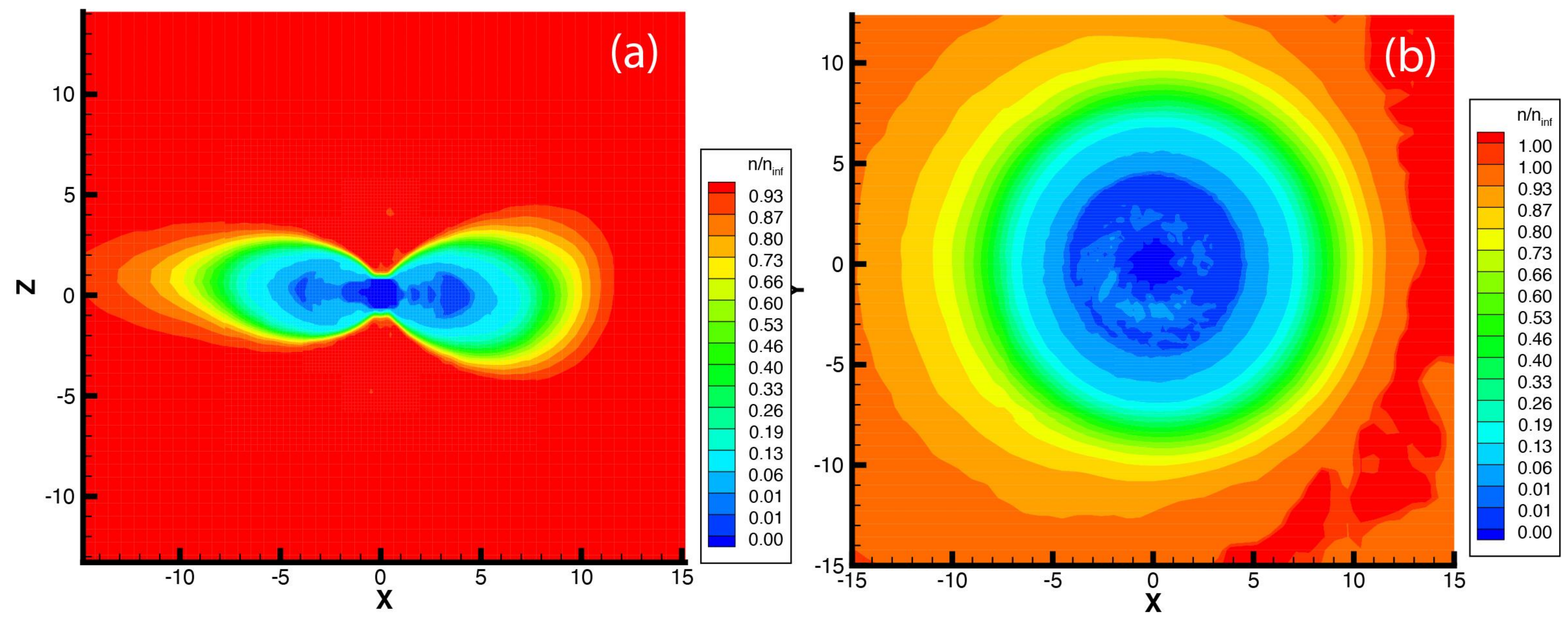
It considers SEPs as test particles that propagate along interplanetary magnetic field lines, and can handle multiple field lines and interpolate the flux and spectrum of particles in the region between them while accounting for isotropic scattering and mean free path. Parker equation or the focused transport equation may be expressed in the Lagrangian coordinates (Sokolov et al 2004, Kota et al 2005)

$$\frac{\partial f}{\partial t}+\mathbf{u}\cdot\nabla f-\frac{1}{3}(\nabla\cdot\mathbf{u})\frac{\partial f}{\partial \log p}=\nabla\cdot(k\cdot\nabla f), \quad k\propto\mathbf{BB}$$

Reduction to single spatial dimension transforms spatially 3-D problem to multitude of spatially 1-D problems

$$\frac{Df}{Dt}+\frac{1}{3}\frac{D\ln\rho}{Dt}\frac{\partial f}{\partial \ln p}=B\frac{\partial}{\partial s}\left(\frac{\varkappa}{B}\frac{\partial f}{\partial s}\right)$$





The calculation was performed for conditions of the geomagnetic storm on March 17, 2015. Example of applying AMPS calculation SEP population in geospace in the SM coordinate frame.} AT quiet time, most particles do not penetrate closer to L=6. While during magnetospheric storms, energetic particles can penetrate as close as L=2, where they get temporarily trapped by the geomagnetic field.