

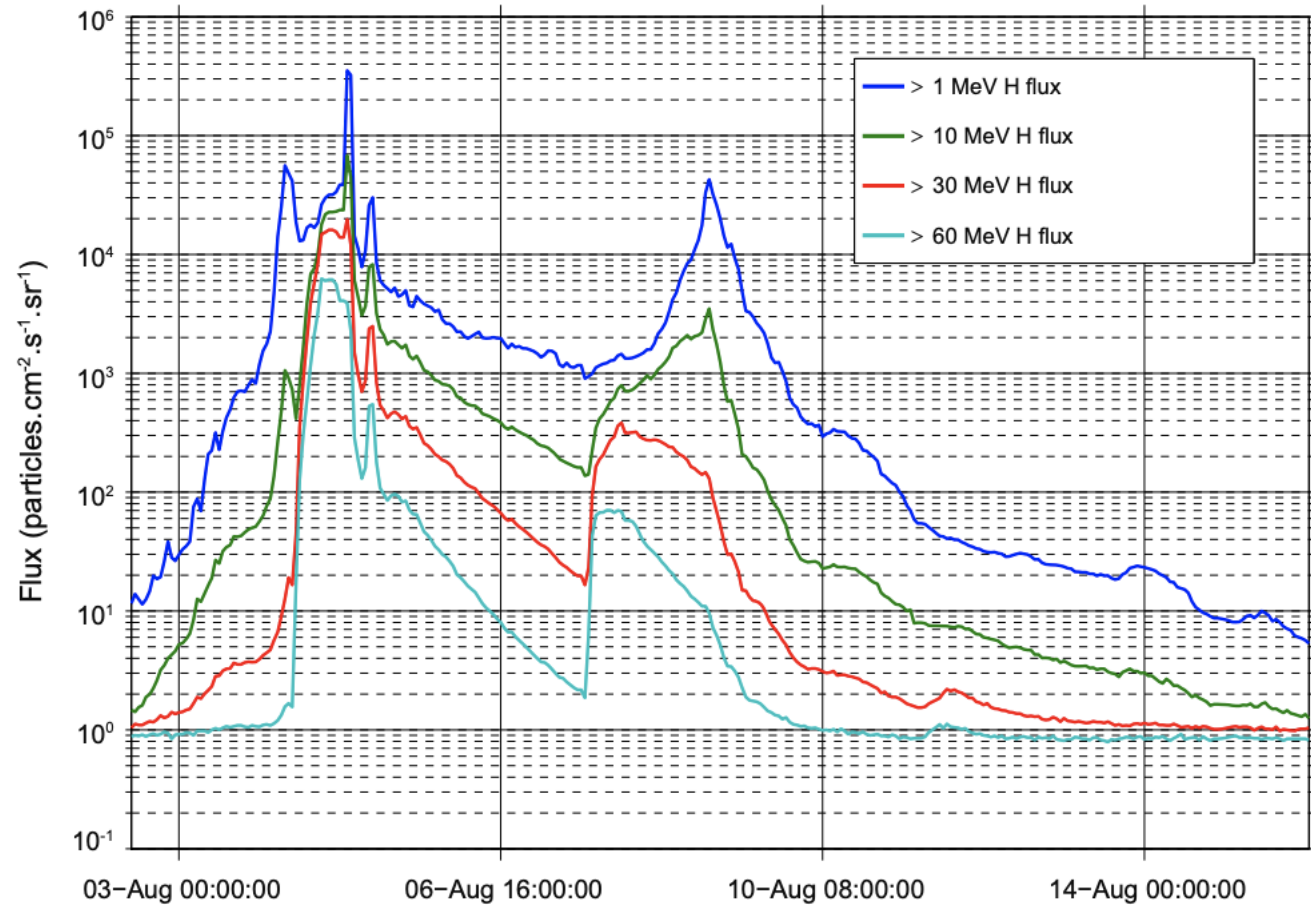
Modeling and Impact of Solar Energetic Particles in the Heliosphere and Geospace

Valeriy Tenishev

Effects due to SEPS in geospace

1. Health risks for astronauts and commercial aviation aircrews
2. Degrade performance and reduce the operational lifetime of spacecraft subjected to radiation
3. Depletion of O₃
4. Enhanced radiation exposure at commercial aviation altitudes
5. Degradation of HF communication

Variability of SEPs

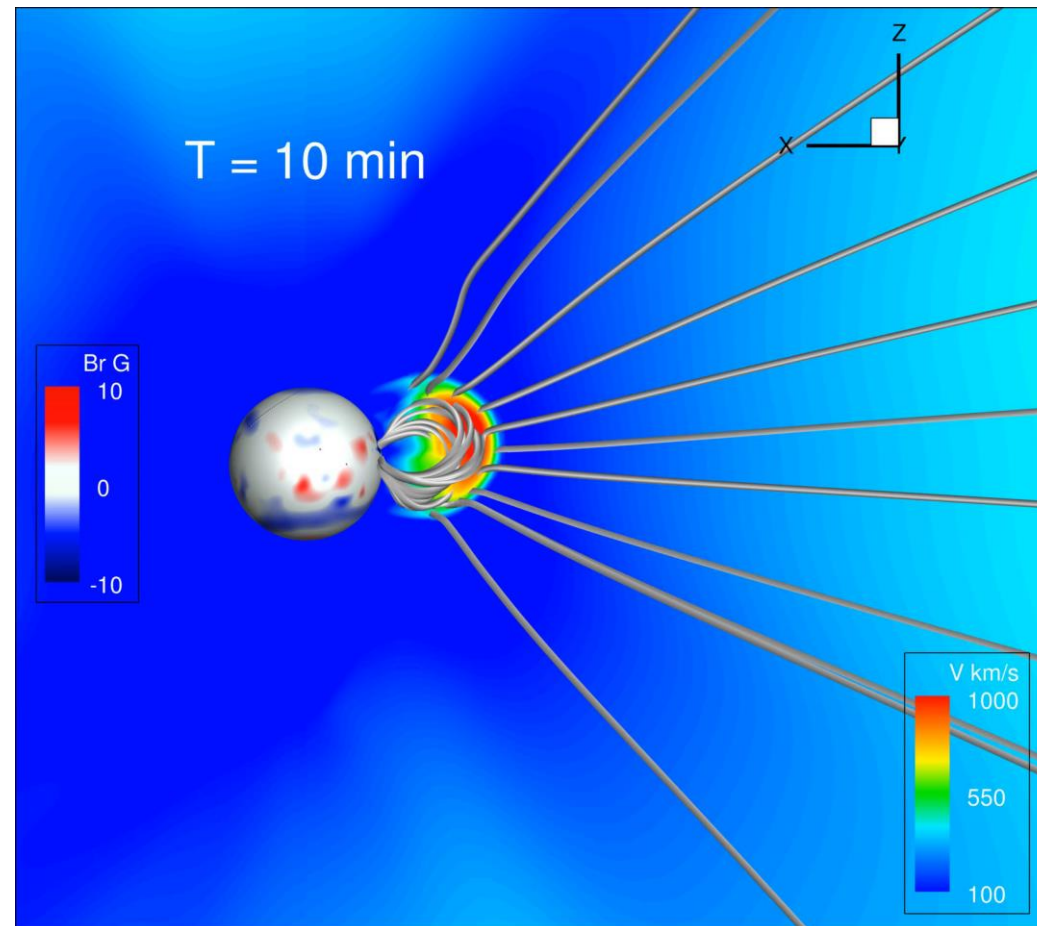


Integral fluxes from the IMP-5 spacecraft were measured during the large August 1972 SPE.

What is the driver? CME

Coronal mass ejections (CMEs)

- Huge bubbles of coronal plasma threaded by intense magnetic field lines that are ejected from the Sun over the course of several hours.



SEPs in the heliosphere: a common approach

Field-aligned transport

1. Near isotropic SEPs

$$\frac{\partial f}{\partial t} + (\mathbf{v}_{sw} \cdot \nabla) f - \frac{1}{3}(\nabla \cdot \mathbf{v}_{sw}) \frac{\partial f}{\partial \ln p} = \nabla \cdot (\mathbf{K} \cdot \nabla f)$$

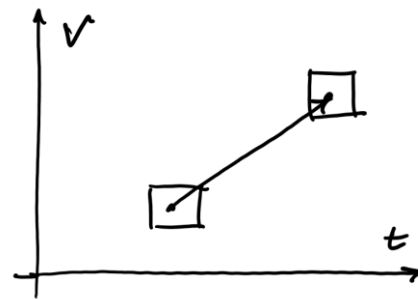
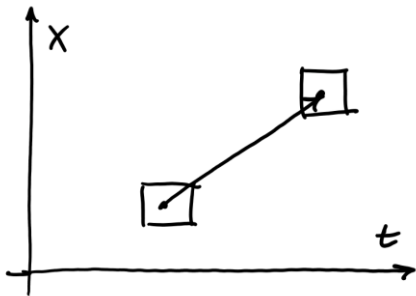
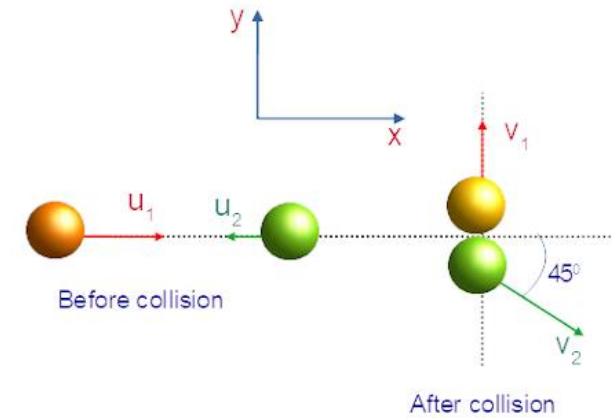
1. Gyro-tropic SEPs

$$\frac{\partial f}{\partial t} + \mu v \frac{\partial f}{\partial z} + \mathbf{V}_{sw} \cdot \nabla f + \frac{dp}{dt} \frac{\partial f}{\partial p} + \frac{d\mu}{dt} \frac{\partial f}{\partial \mu} - \frac{\partial}{\partial \mu} \left(D_{\mu\mu} \frac{\partial f}{\partial \mu} \right) = Q,$$

How does it work?

- Boltzmann equation

$$\frac{\partial f}{\partial t} + \mathbf{v} \frac{\partial f}{\partial \mathbf{x}} + \mathbf{a} \frac{\partial f}{\partial \mathbf{v}} = \frac{\delta f}{\delta t}$$



Particle acceleration 1

$$\frac{\partial f}{\partial t} + (\mathbf{v}_{\text{sw}} \cdot \nabla) f - \boxed{\frac{1}{3}(\nabla \cdot \mathbf{v}_{\text{sw}}) \frac{\partial f}{\partial \ln p}} = \nabla \cdot (\mathbf{K} \cdot \nabla f)$$

$$\nabla \cdot \mathbf{V}_{\text{sw}} = -d \ln \rho / dt$$

Particle acceleration 2

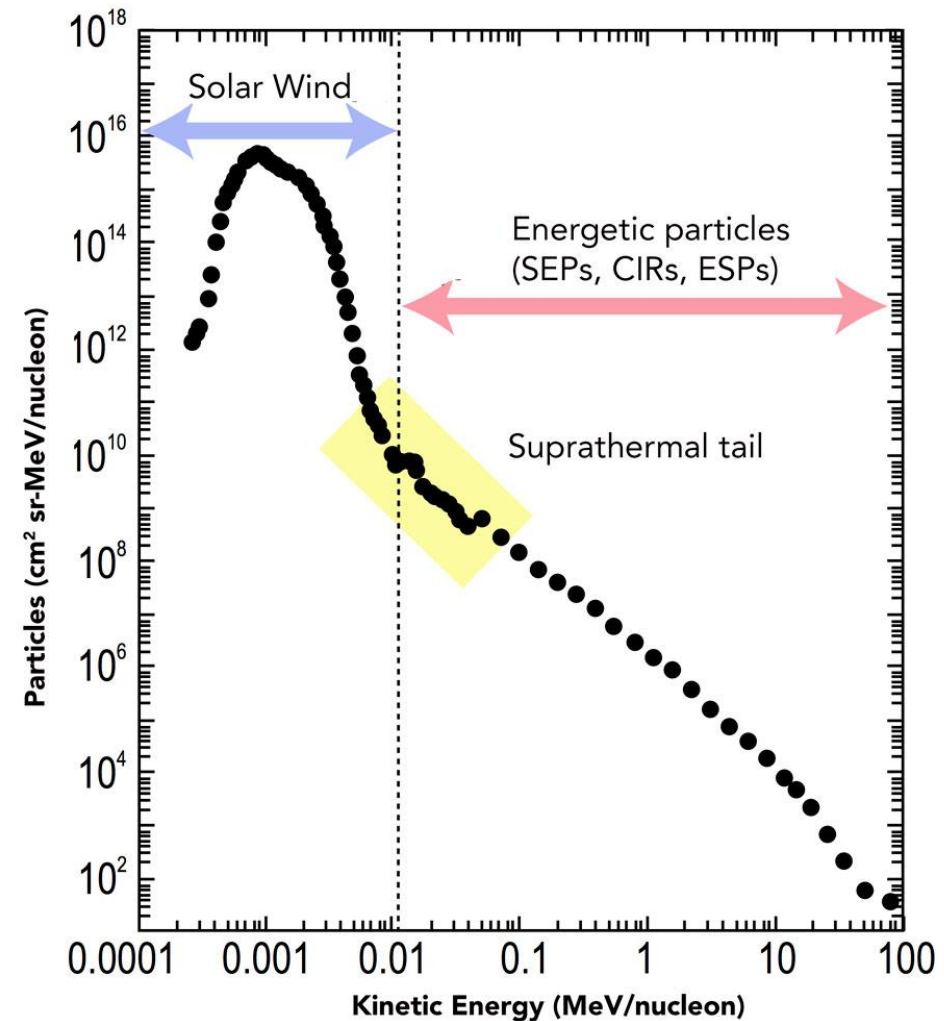
$$\left(\frac{\delta f}{\delta t}\right)_{scat} = \sum_{+,-} \frac{\partial}{\partial \mu_{\pm}} \left(D_{\mu\mu}^{\pm} \frac{\partial f}{\partial \mu_{\pm}} \right) \longrightarrow \frac{\partial}{\partial \mu} \left(D_{\mu\mu} \frac{\partial f}{\partial \mu} \right)$$

$$D_{\mu\mu}^{\pm} = \frac{v}{\lambda_{\mu\mu}^{\pm}} (1 - \mu^2) |\mu|^{2/3}$$

$$\lambda_{\mu\mu}^{\pm} = \frac{6}{\pi} \frac{B^2}{\mu_0 w_{\pm}} r_L^{\frac{1}{3}} \left(\frac{L_{max}}{2\pi} \right)^{2/3}$$

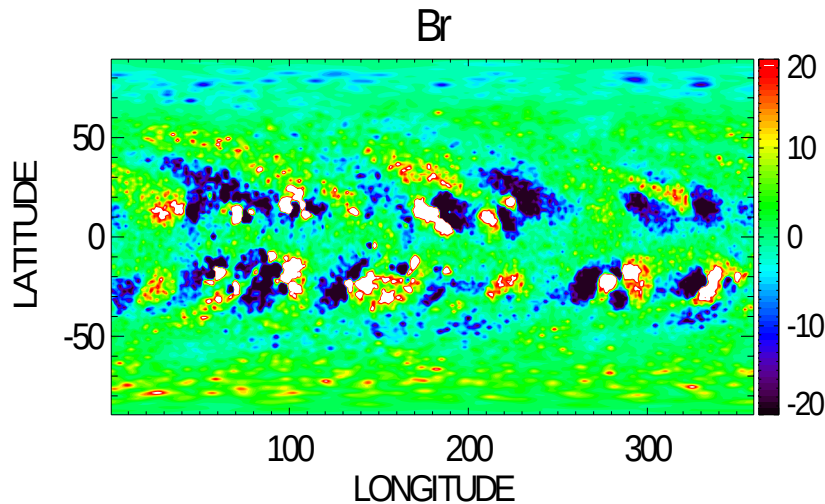
Seed population

- **Supra-thermal particles source:** Solar flares, Preceding SEPs , large-scale turbulence
 - Solar flares can serve as the seed population for diffusive shock acceleration (DSA).
 - Seed population at the front of a CME-driven shock: Injected in the DSA
- **Modeling:**
 - Parker or focused transport equations
 - Alfvén-Wave-driven Solar Atmosphere Model (AWSOM)
 - Stochastic acceleration of supra-thermal particles

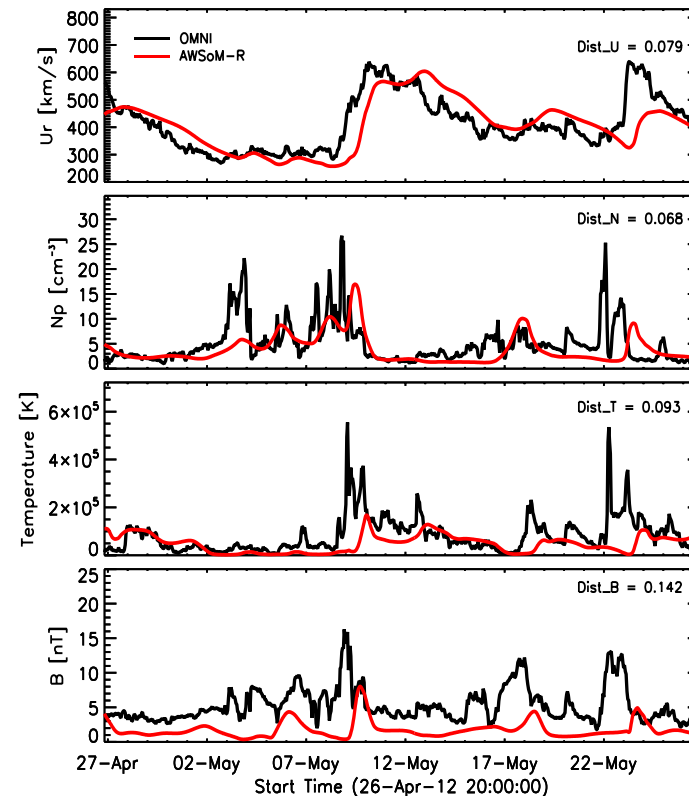


Input and Output of AWMoM/AWMoM-R

AWMoM and AWMoM-R take the observed photospheric magnetic field as an input and generate the macroscopic quantities (density, velocity and pressure) and the magnetic field in the simulation domain (from the surface of the Sun through the inner heliosphere when AWMoM/AWMoM-R is coupled with an inner heliosphere model).

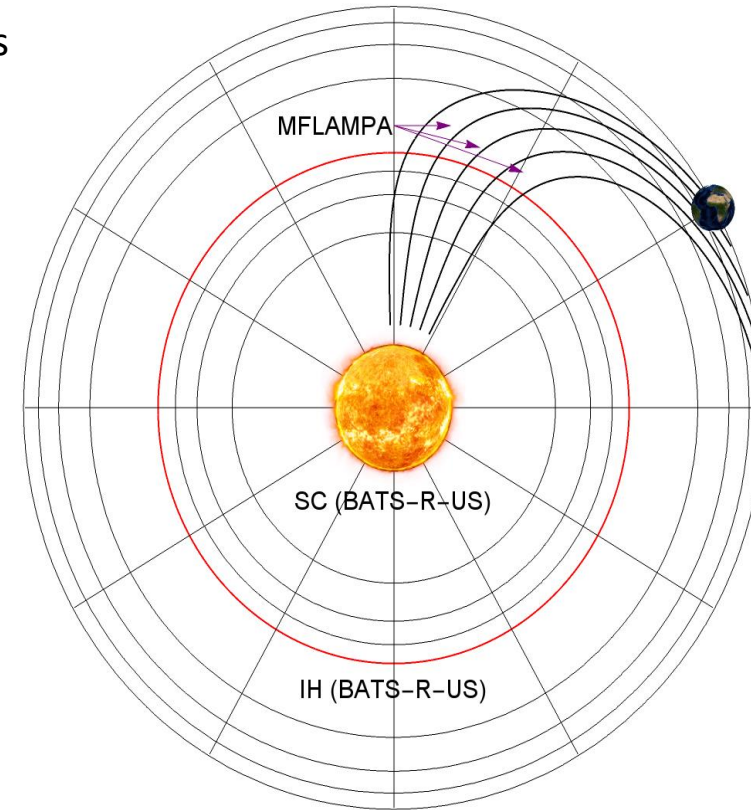
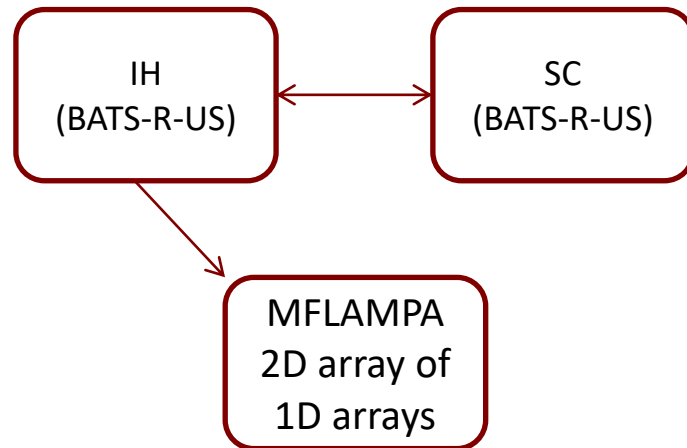


We simulate the 2012-05-17 CME event. The left figure is the input magnetogram and the right figure shows the 1 AU data model comparison for the background wind.



Extracting Evolving Magnetic Field Lines

- Models of Solar Corona and Heliosphere
- Block-Adaptive-Tree-Solar-wind-Roe-type-Upwind-Scheme (BATS-R-US), one (for Heliosphere), or two (plus SC) or three (plus outer heliosphere)



- Kinetic particle model: 2D multitude of 1D particle ensembles driven by 2D multitude of 1D distributions of MHD parameters

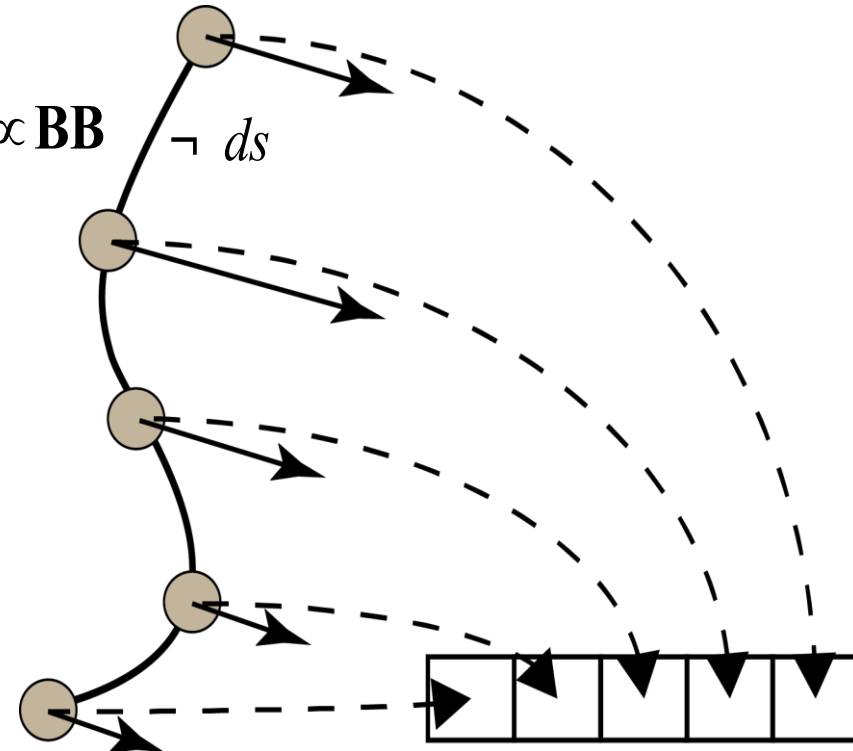
Adaptive Mesh Particle Simulator (AMPS)

Parker equation or the focused transport equation may be expressed in the Lagrangian coordinates (Sokolov et al 2004, Kota et al 2005)

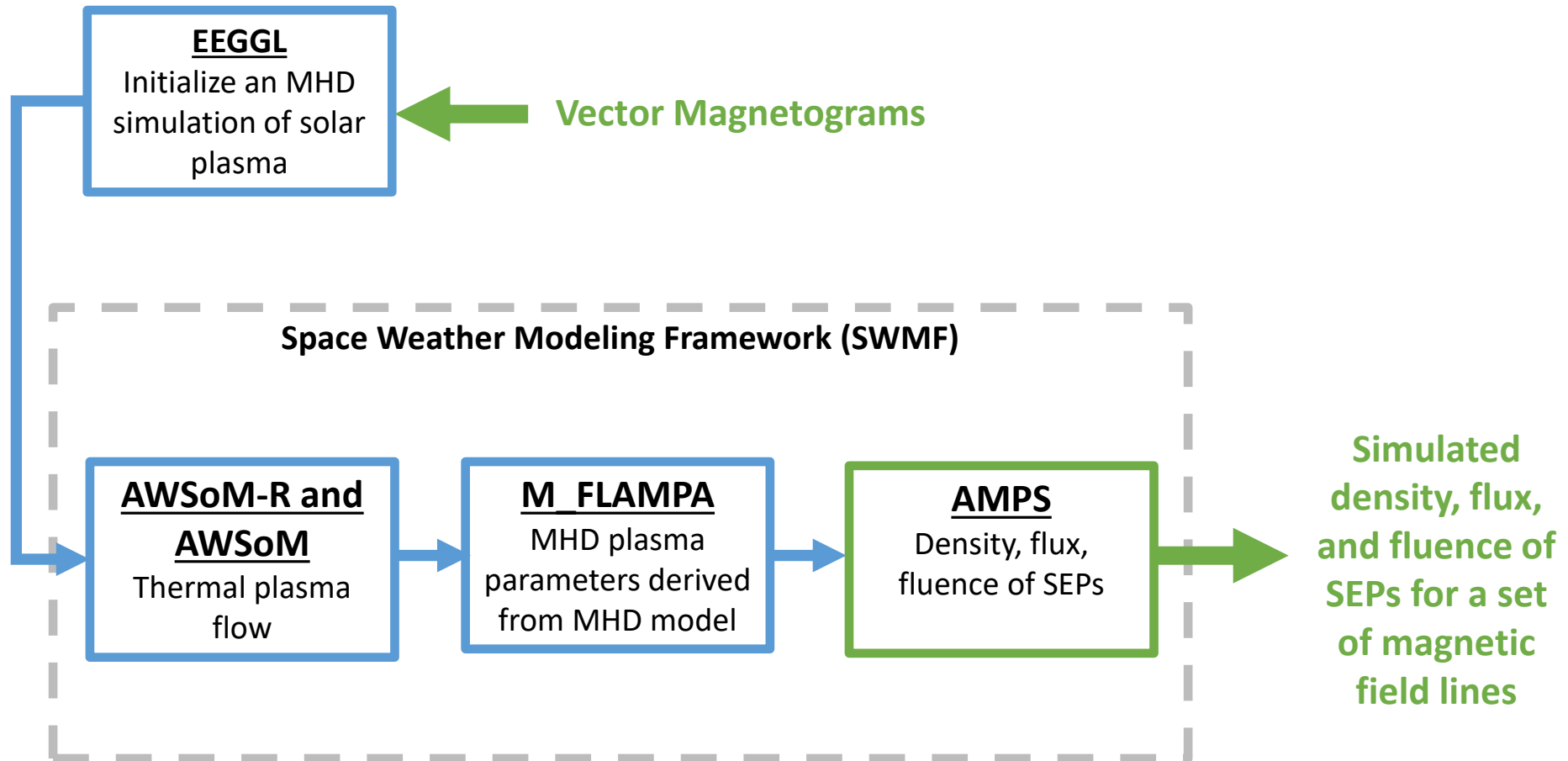
$$\frac{\partial f}{\partial t} + \mathbf{u} \cdot \nabla f - \frac{1}{3} (\nabla \cdot \mathbf{u}) \frac{\partial f}{\partial \log p} = \nabla \cdot (k \cdot \nabla f), \quad k \propto \mathbf{B}\mathbf{B}$$

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

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

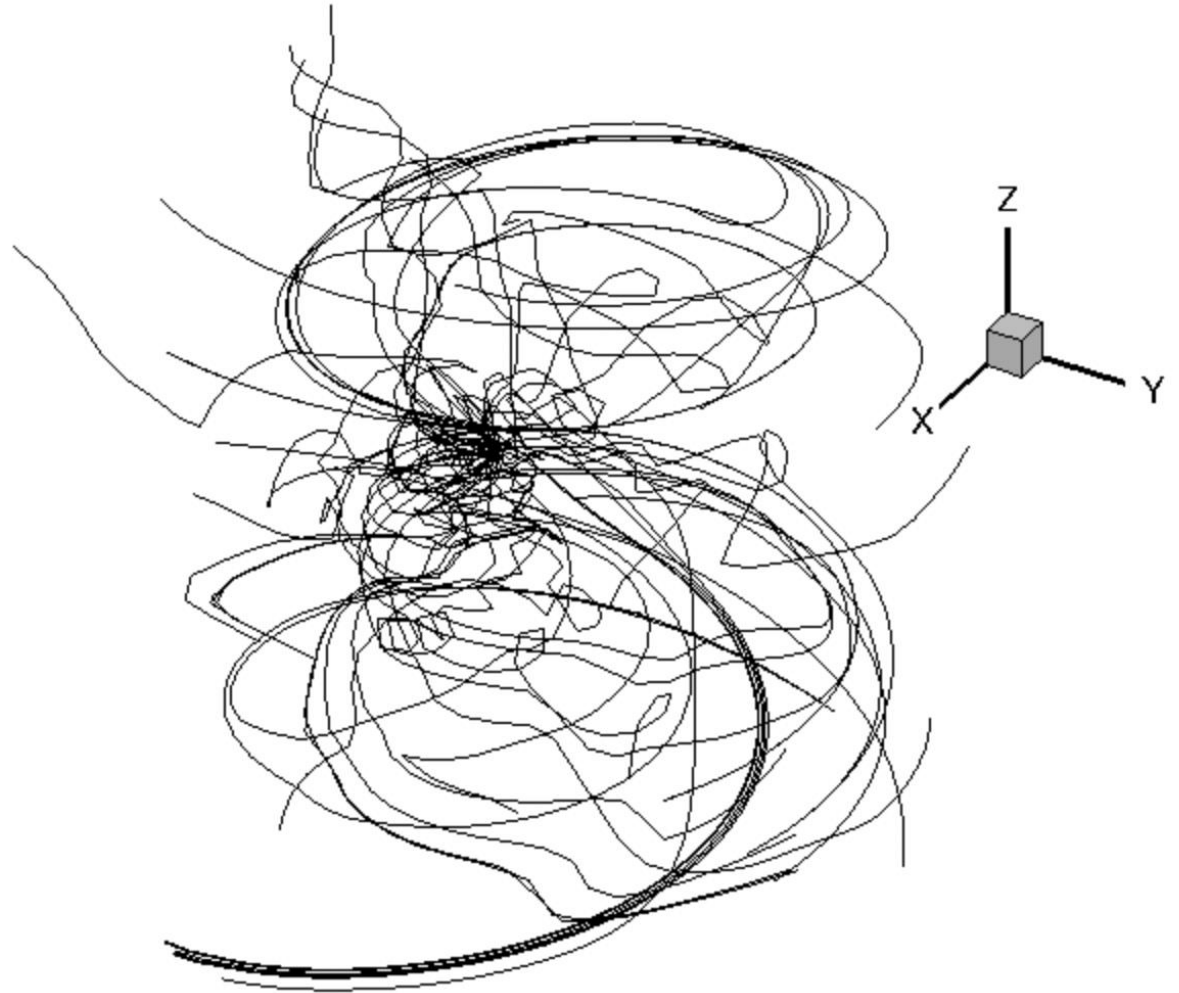


SEPs in AMPS: workflow



SEPs in AMPS: Current status

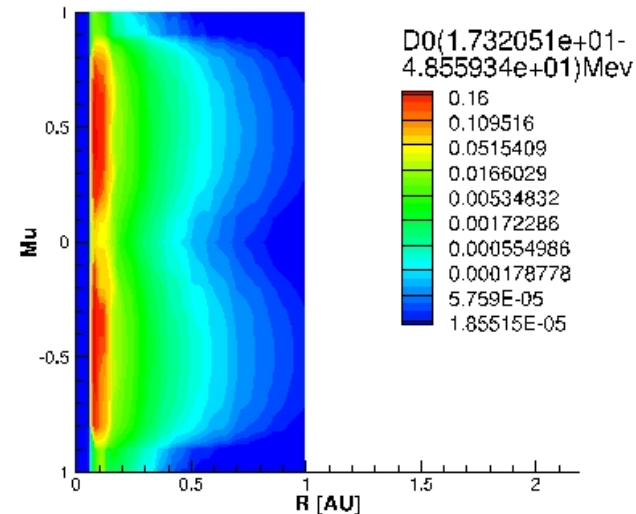
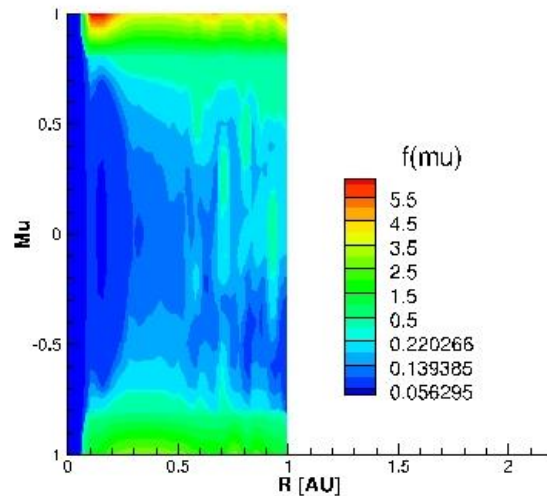
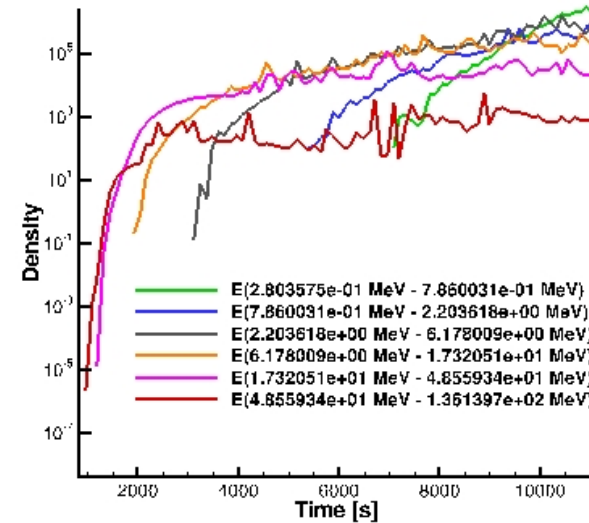
- Magnetic field lines are derived from 3D MHD modeling of plasma in the heliosphere (top panel), but modeling SEP transport is reduced to a 1D problem



SEPs in AMPS: Current status

Example:

1. Seed population $f \sim p^{-5}$
2. Sun-to-Earth:
 - Coupled SWMF/SC, SWMF/IH, SWMF/M-FLAMPA, SWMF/AMPS



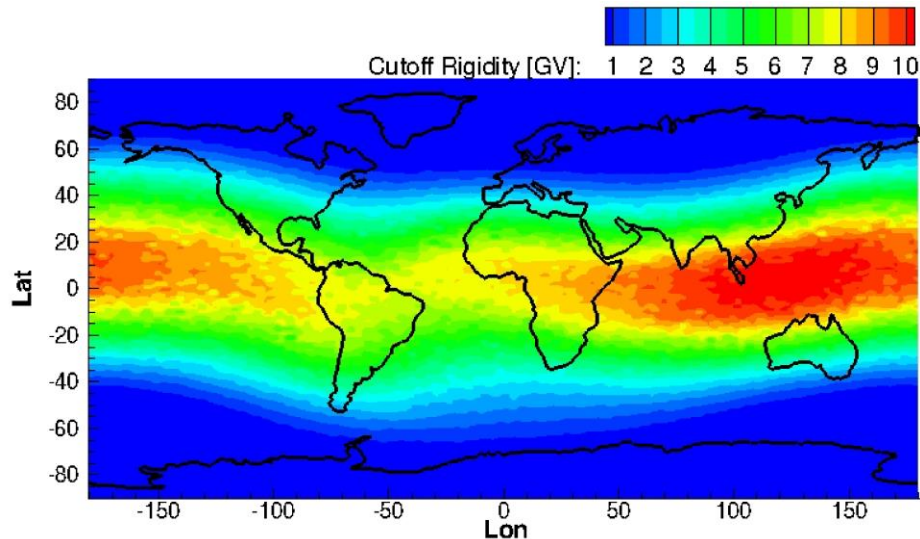
Radiation in geospace

1. Health risks for astronauts and commercial aviation aircrews
2. Degrade performance and reduce the operational lifetime of spacecraft subjected to radiation
3. Depletion of O₃
4. Enhanced radiation exposure at commercial aviation altitudes
5. Degradation of HF communication

Radiation in geospace: rigidity cutoff

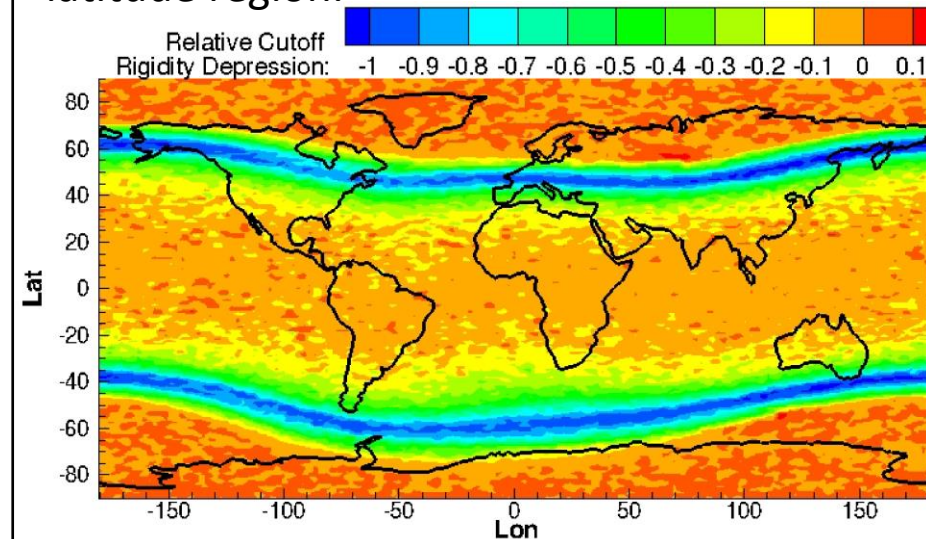
Rigidity cutoff map

1. The map is calculated for an altitude of 500 km.
2. Rigidity cutoff map calculated for quiet geomagnetic conditions.



Suppression of the rigidity cutoff during a geomagnetic storm.

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.



Geomagnetic rigidity cutoff

$$R_C = \frac{M \cos^4 \lambda}{r^2 [1 + (1 - \sin \epsilon \sin \xi \cos^3 \lambda)^{1/2}]^2}$$

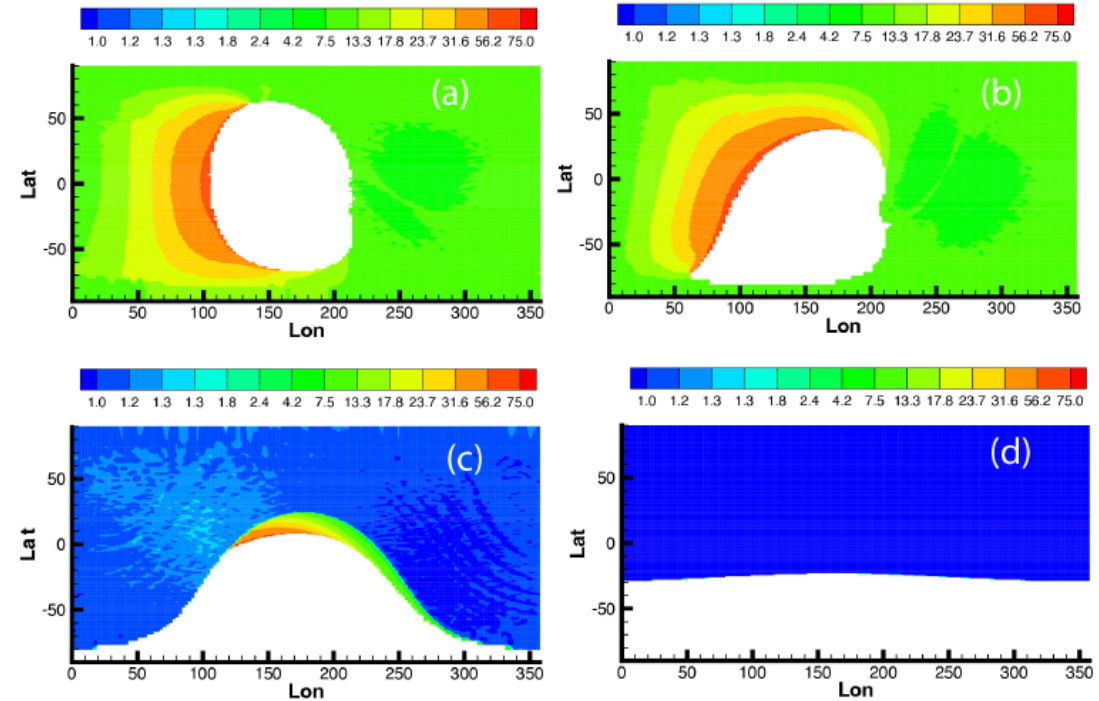


Figure 4. Example of applying AMPS for calculation direction rigidity cutoff. The map is calculated for an altitude of 500 km. The cutoff is calculated at the location in the x-z plane of SM coordinate frame when the vector connecting the point and the center of the frame of reference is 0° (panel a), 20° (panel b), 60° (panel c), and 90° (panel d). That corresponds to locations $\mathbf{x} = (6.87 \times 10^3 \text{ km}, 0, 0)$, $\mathbf{x} = (5.95 \times 10^3 \text{ km}, 0, 3.45 \times 10^3 \text{ km})$, $\mathbf{x} = (3.45 \times 10^3 \text{ km}, 0, 5.95 \times 10^3 \text{ km})$, and $\mathbf{x} = (0, 0, 6.87 \times 10^3 \text{ km})$, respectively. The figure illustrates the effect of the Earth's shadowing, and the effect of the east-west asymmetry (panels a,b,c).

Geomagnetic rigidity cutoff

$$R_C = \frac{M \cos^4 \lambda}{r^2 [1 + (1 - \sin \epsilon \sin \xi \cos^3 \lambda)^{1/2}]^2}$$

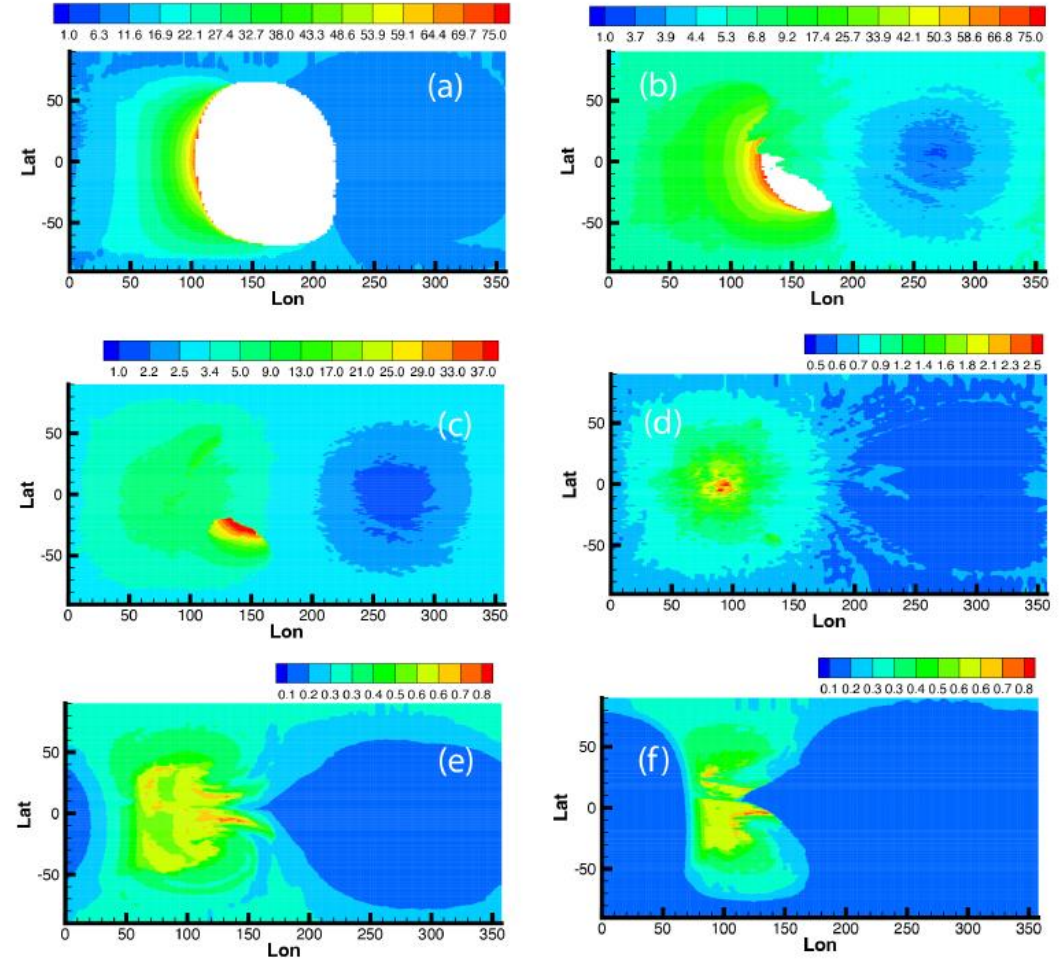
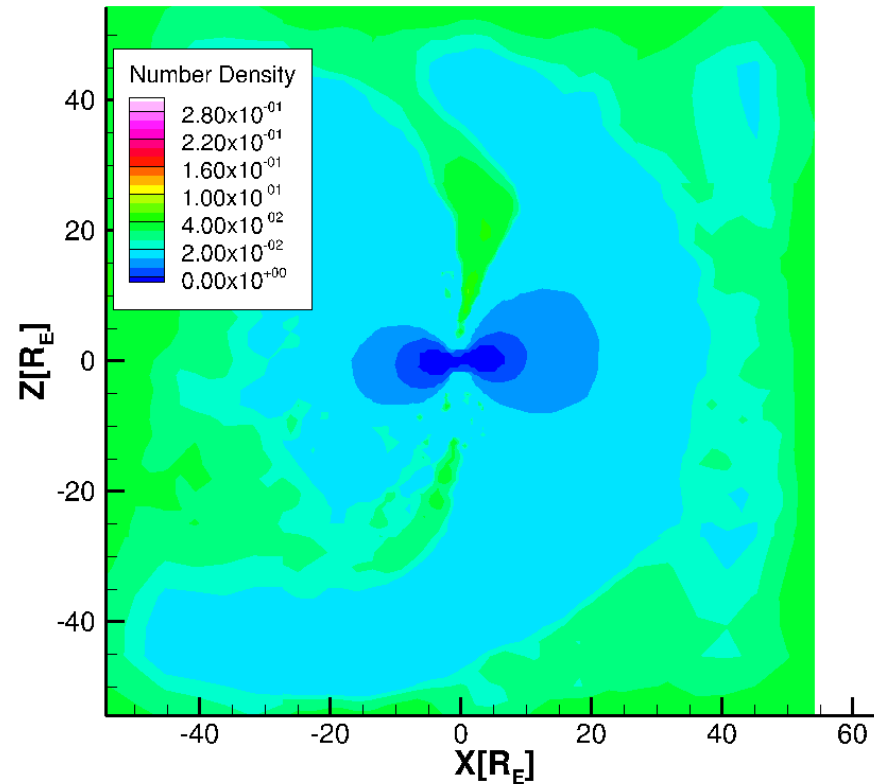


Figure 3. The figure illustrates the directional dependence of the calculated rigidity cutoff. The rigidity cutoff is calculated at $x = (6.771 \times 10^3 km, 0, 0)$, $x = (9.55 \times 10^3 km, 0, 0)$, $x = (1.27 \times 10^4 km, 0, 0)$, $x = (2.55 \times 10^4 km, 0, 0)$, $x = (5.1 \times 10^4 km, 0,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

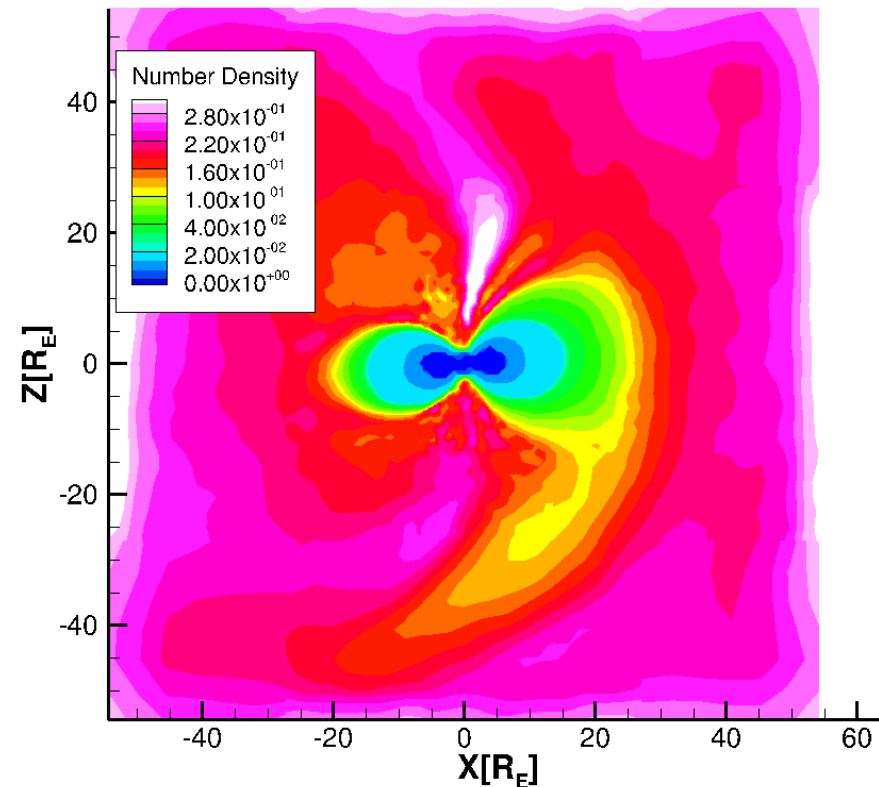
Simulated distribution of SEPs in geospace

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

Density of the energetic particles increased by an order of magnitude

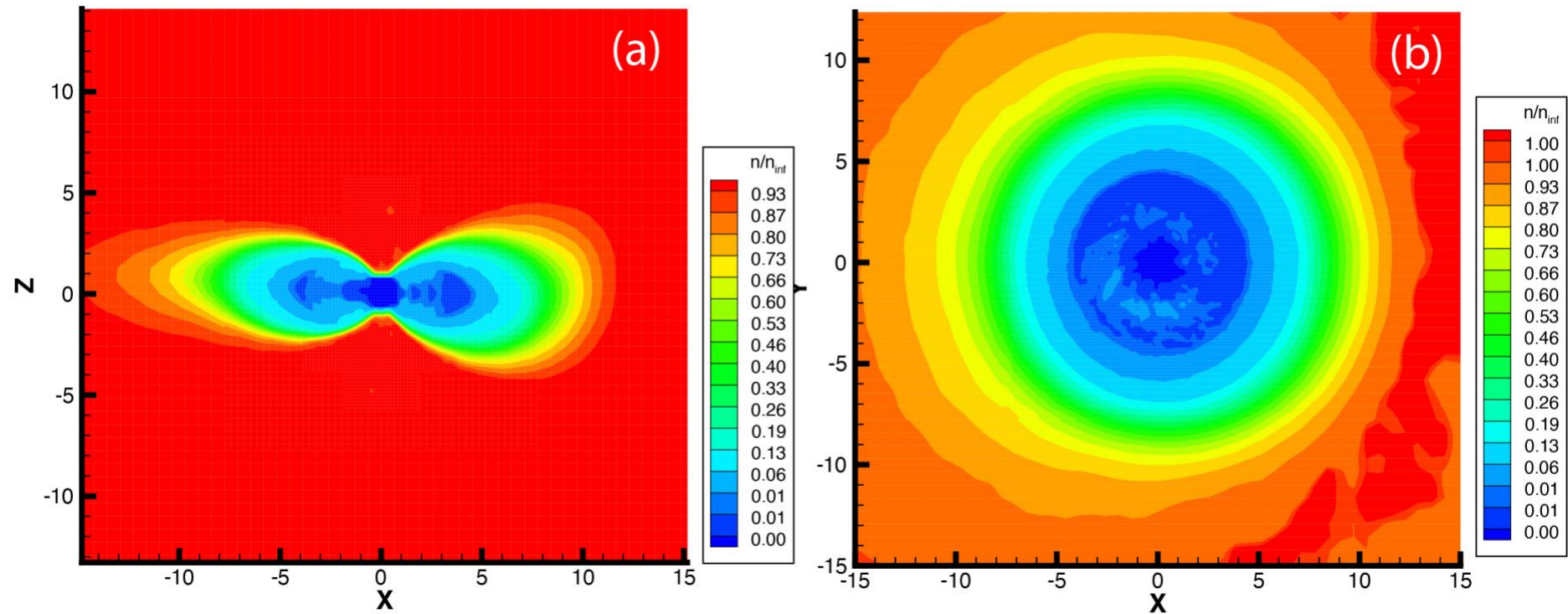


Before the event

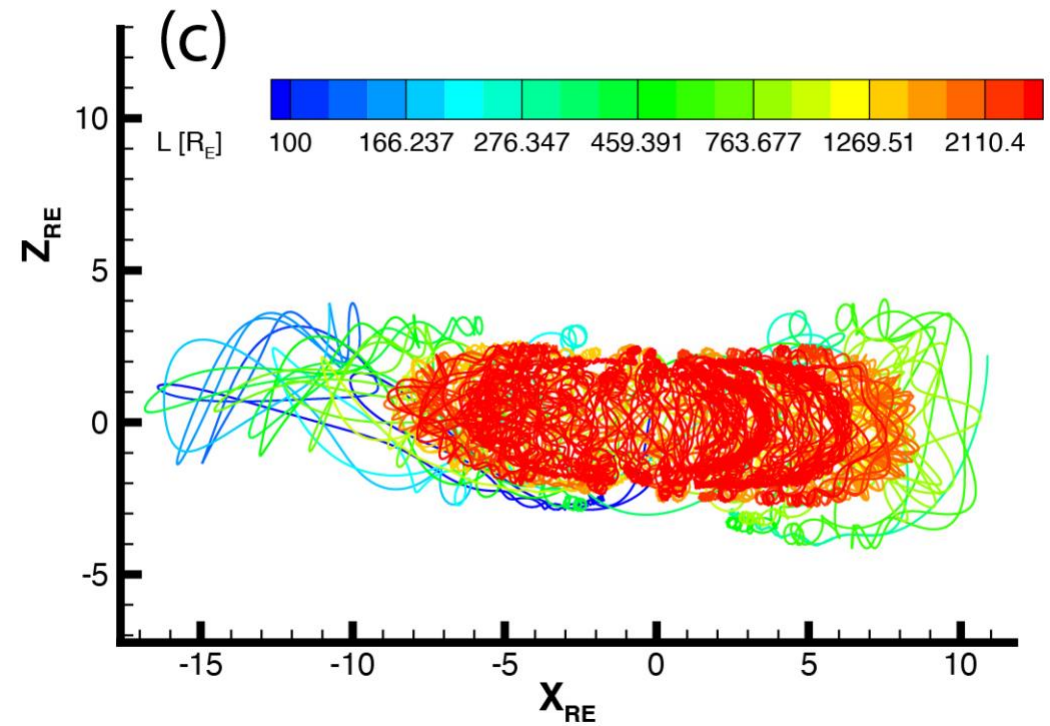
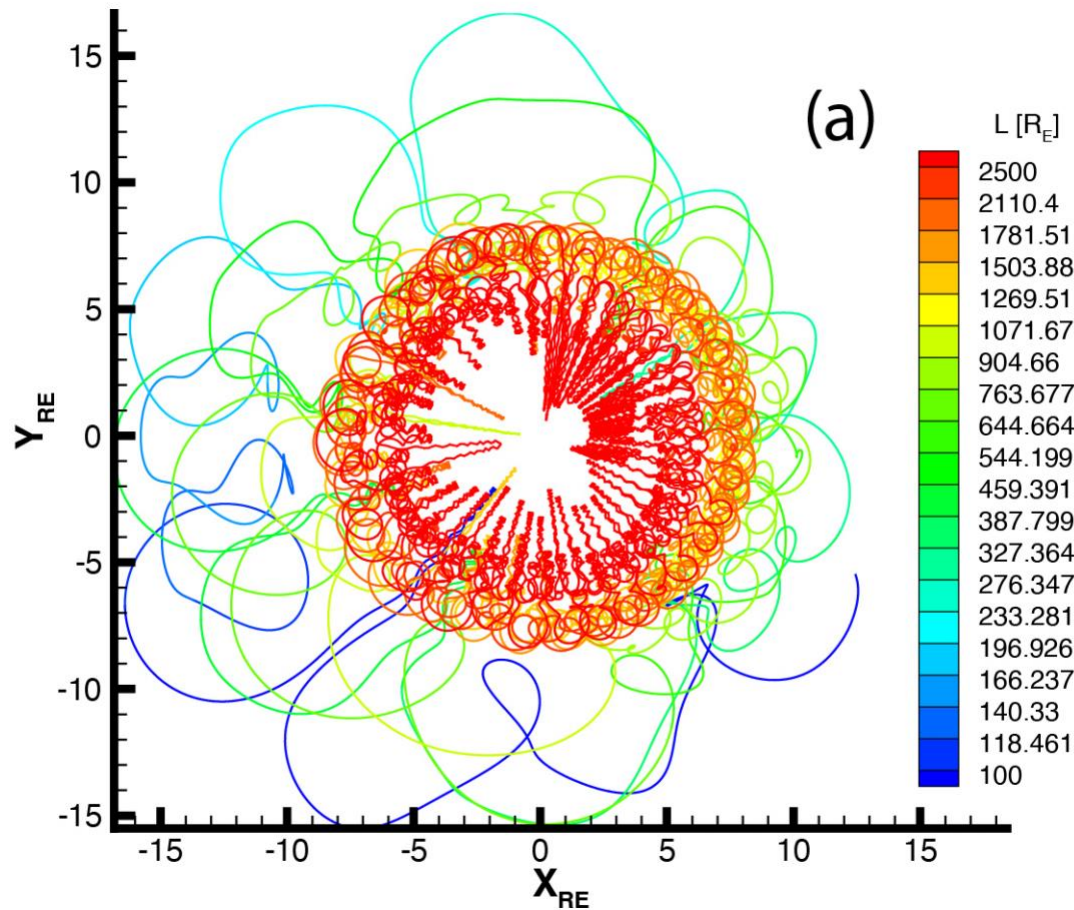


Main phase of the event

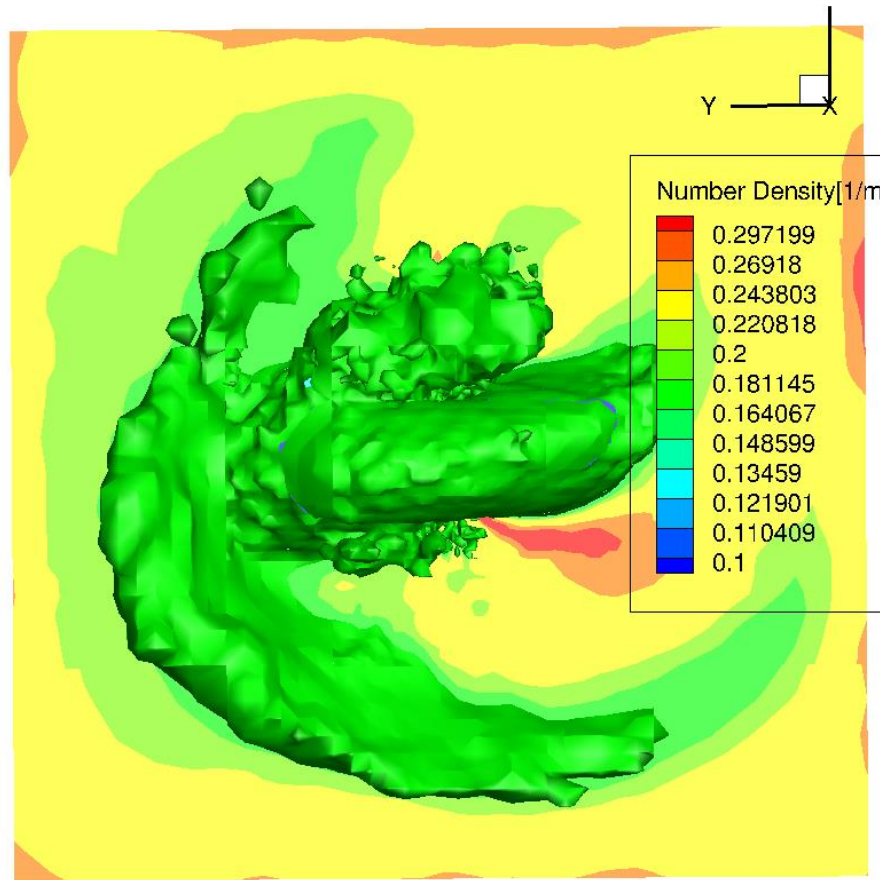
Transport and SEPs in the geospace



Transport and SEPs in the geospace



Conclusion



Structure of energetic particles' density in geospace

- Kinetic effects dominates distribution of energetic particles in geospace
- Combination of SWMF/AMPS + SWMF/BATSRUS codes provides capabilities for modeling SEPs and GCRs in geospace
- The content of SEPs can exhibit a major density increase during a SEP event