Solar Energetic Particles: Acceleration and Transport in Realistic Magnetic Fields

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Solar Energetic Particles: How to Predict and to Mitigate Hazards?

Motivation:

- The high-energy protons produce a real radiation hazards on board manned and unmanned spacecraft

We incorporate the following models:

- Only particles of a particular range of energies are important: (10 -50) MeV.
- Magnetic connectivity problem is of crucial importance. The realistic magnetic field in solar corona and inner helioshere at $(1 \div 216) R_s$ needs to be involved
- Magnetic field observations should be incorporated.
- As long as the particles are believed to be accelerated by the shock wave, which are driven by Coronal Mass Ejections, the CME model should be included and the dynamical model for the heliosphere and the solar corona should properly describe strong shocks (conservative, shock capturing schemes, full equation of energy)
- At least two kinetic models are needed for the SEP acceleration and transport
  - For acceleration from the injection energy to the multi-MeV range: quasi-1-D field-line-advection model (FLAMPA) extracts the MHD parameters along the moving magnetic field line and integrates the kinetic equation along this line. The Parker equation (for isotropic distribution function of time, energy and coordinate along the magnetic field line) or the University of Arizona model (Kota,2005), for a gyrotropic distribution function are employed
  - For particle propagation to 1 AU (or toward the spacecraft) only the Monte-Carlo approach allows to take the transversal motion into account (orbiting and transversal diffusion).

SEPs in Human Life

- Setup for evaluating the SEP influence consists of an astronaut body, shielded by the "standard screen" of stopping length of $\rho d = 0.54$ g/cm^2 (Al, 2 mm), $Z/A = 13/27$
- Fast proton motion through the "screen" is governed by:

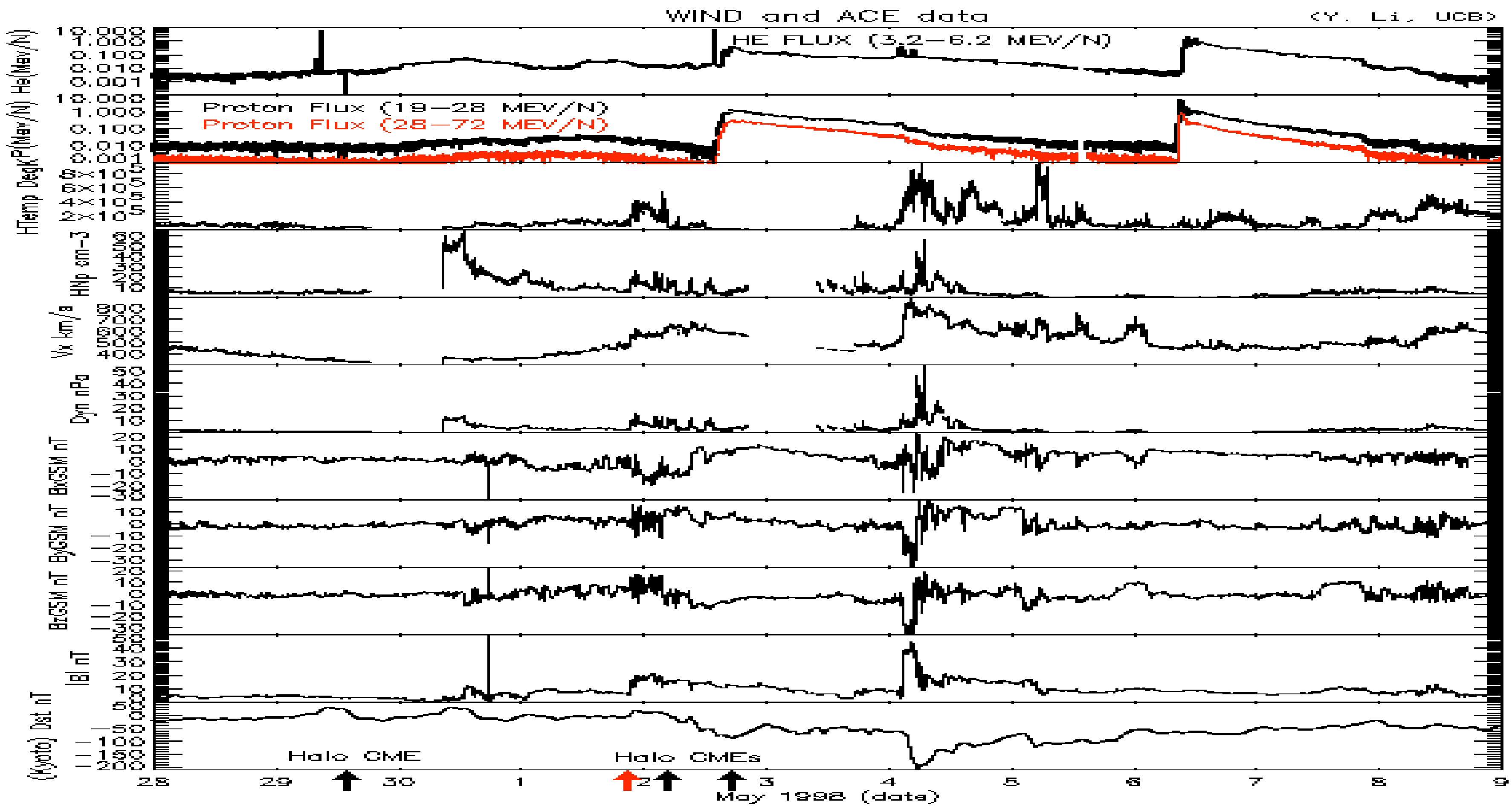
$$\frac{dE(p)}{ds} = -\nu_{ie}(p)p, \nu_{ie}(p) \propto p^{-3}, \rho d = \frac{1}{4}(A/Z)\frac{p_0}{(\nu_{ie}(p_0)/n_e)}$$

- From here, the vitally important range of SEP energies is:

$$E > \sqrt{\frac{Z}{A}\frac{4\pi e^4(\rho d)\Lambda}{m_e}} \approx \sqrt{\Lambda}\cdot 8.5 MeV \approx 20 MeV$$

- The spectrum of SEPs decays with the energy. Thus, the particles of lower energy are less dangerous, since they are screened, the particles of higher energy, are less dangerous, since their flux is small.
- Protons of energies >100 MeV are less dangerous and usually reach the observer earlier (alert?)

SEP Measurements for April-May 1998 Events



Quasi-1D Kinetic Equation.

- Consider as an example a diffusive kinetic equation (Parker,1966) governing the Diffuse-Shock-Acceleration Mechanism: THIS IS A 3D EQUATION

$$\frac{\partial f}{\partial t} + \mathbf{u}\cdot\nabla f = \nabla\cdot(\mathbf{D}\cdot\nabla f) + \frac{p}{3}\frac{\partial f}{\partial p}\nabla\cdot\mathbf{u}$$

- Here ***f*** is an isotropic part of the SEP distribution function, ***u*** is the bulk plasma velocity, ***D*** is the diffusion tensor.
  - Assume that the diffusion only occurs along the magnetic field line: $\mathbf{D} = D\mathbf{n}_B\mathbf{n}_B, \nabla\cdot(B\mathbf{n}_B) = 0.$
  - Assume the magnetic field to be frozen into the plasma
  - Introducing the Lagrangian coordinates along the magnetic field line, the kinetic equation can be written for each magnetic line separately:

$$\frac{df}{dt} = B\frac{\partial}{\partial s}\left(\frac{D}{B}\frac{\partial f}{\partial s}\right) - \frac{1}{3}\frac{d\ln\rho}{dt}\frac{\partial f}{\partial \ln p}, \quad ds^2 = d\mathbf{x}^2$$

where ρ is the plasma density: $\frac{\partial\rho}{\partial t} + \nabla\cdot(\rho\mathbf{u}) = 0, \quad \frac{d\ln\rho}{dt} = -\nabla\cdot\mathbf{u}$

- Note: the transformed equation depends on A SINGLE COORDINATE (quasi-1D). At the same time, full 3D field geometry is not dismissed!

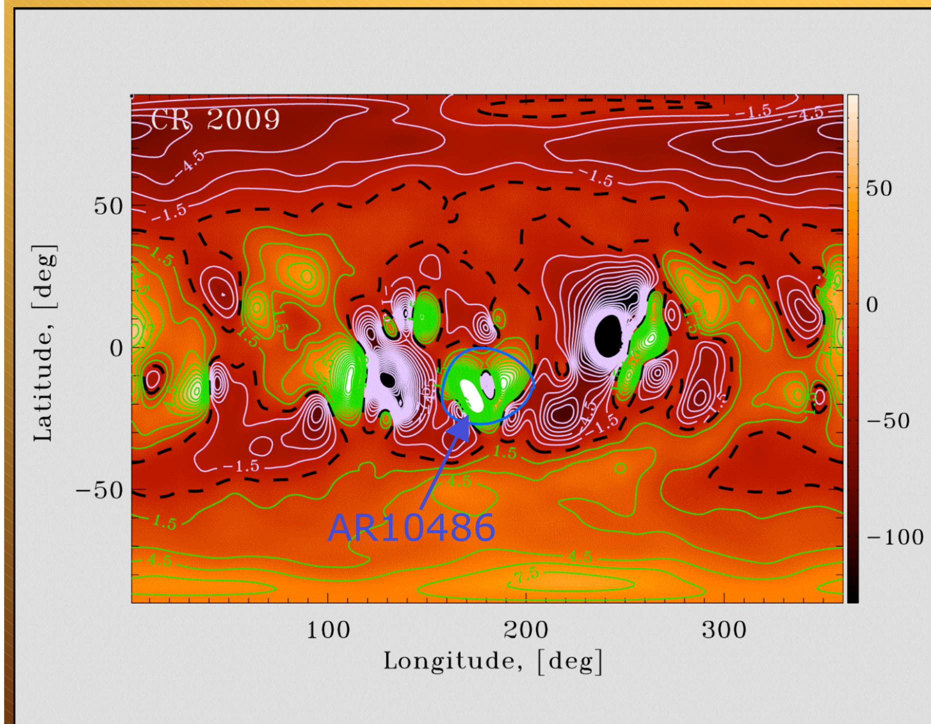
Field-Line-Advection Model for Particle Acceleration.

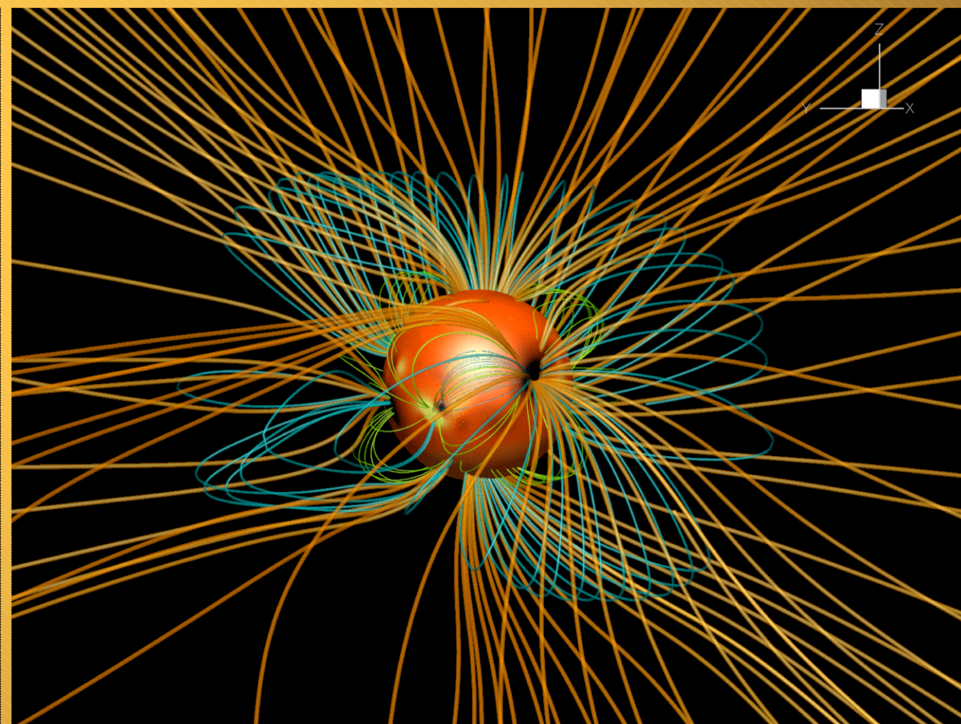
- Why the Lagrangian coordinates are so effective? This is because we assume the SEP particles moving ALONG the magnetic field line, why the Lagrangian meshes (=fluid particles) move TOGETHER WITH the frozen in magnetic field line.
- Note: we need frequent dynamical coupling to MHD. We trace the Lagrangian meshes along the magnetic field line(s), and extract the MHD parameters at these meshes. Thus we obtain the dynamic coefficients in the kinetic equation. After each coupling we advance the solution of the kinetic equation, what can be easily done for quasi-1D equation.
- The FLAMPA approach also works for the Scilling equation (see J.Kota's presentation). NEW OBSERVATION: it also works for the transport equation describing the Alfven wave turbulence.

Full-disk MDI Magnetograms Drive MHD Simulations

Map of B_R (potential field) at R=1.10R_S on Oct 27 (order of harmonics n=90)

Computed coronal magnetic field (non-potential) at steady-state with solar wind





How we Incorporate the Observed Field

In collaboration with Yang Li

- The coronal magnetic field is recovered from observations using the following assumptions

$$\vec{B} = -\nabla\Phi, \quad \Phi = \sum_{n=1}^{\infty} \frac{a_{nm} Y_{nm}(\cos\theta, \varphi)}{(R/R_S)^{n+1}},$$

$$B_{R|R=R_s} = B(observed)$$

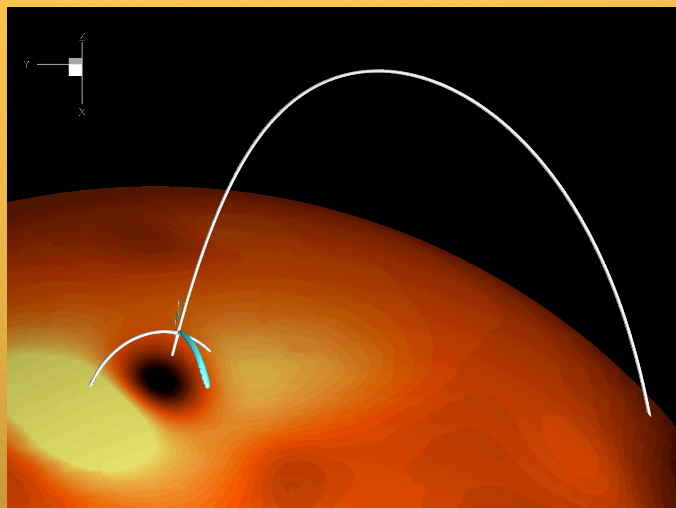
- We do not assume the potential magnetic field in our simulations and employ the observed magnetic field in the following manner

$$\vec{B} = \vec{B}_0 + \vec{B}_1, \quad \vec{B}_0 = -\nabla\Phi, \quad B_{R|R=R_s} = B_{0R|R=R_s}$$

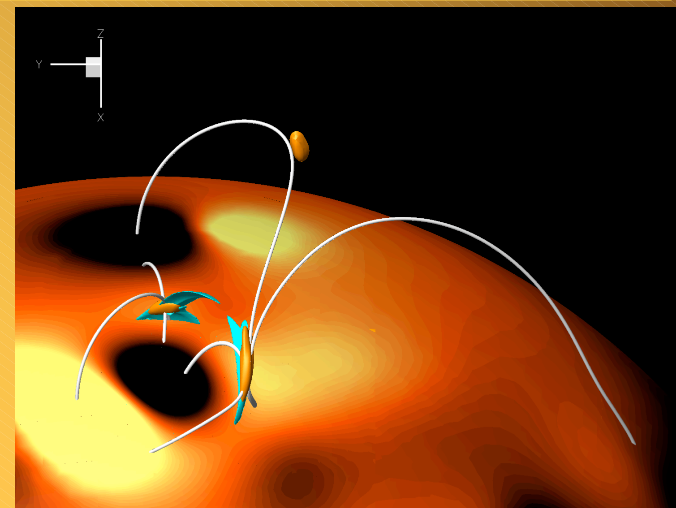
- The "observed" potential field is thus used for driving the MHD system with the full induction equation

$$\frac{\partial \vec{B}_1}{\partial t} + \nabla \bullet \left(\vec{u} \otimes (\vec{B}_0 + \vec{B}_1) - (\vec{B}_0 + \vec{B}_1) \otimes \vec{u} \right) = 0$$

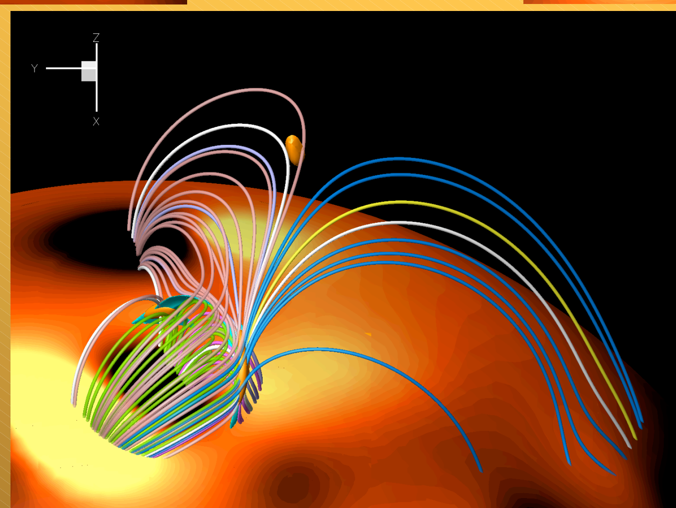
Global AND Local Magnetogramms Prior to an Eruption are Needed.



32 hours later



If the patterns are that different, then what can we do with limb events (with no local magnetogramm?

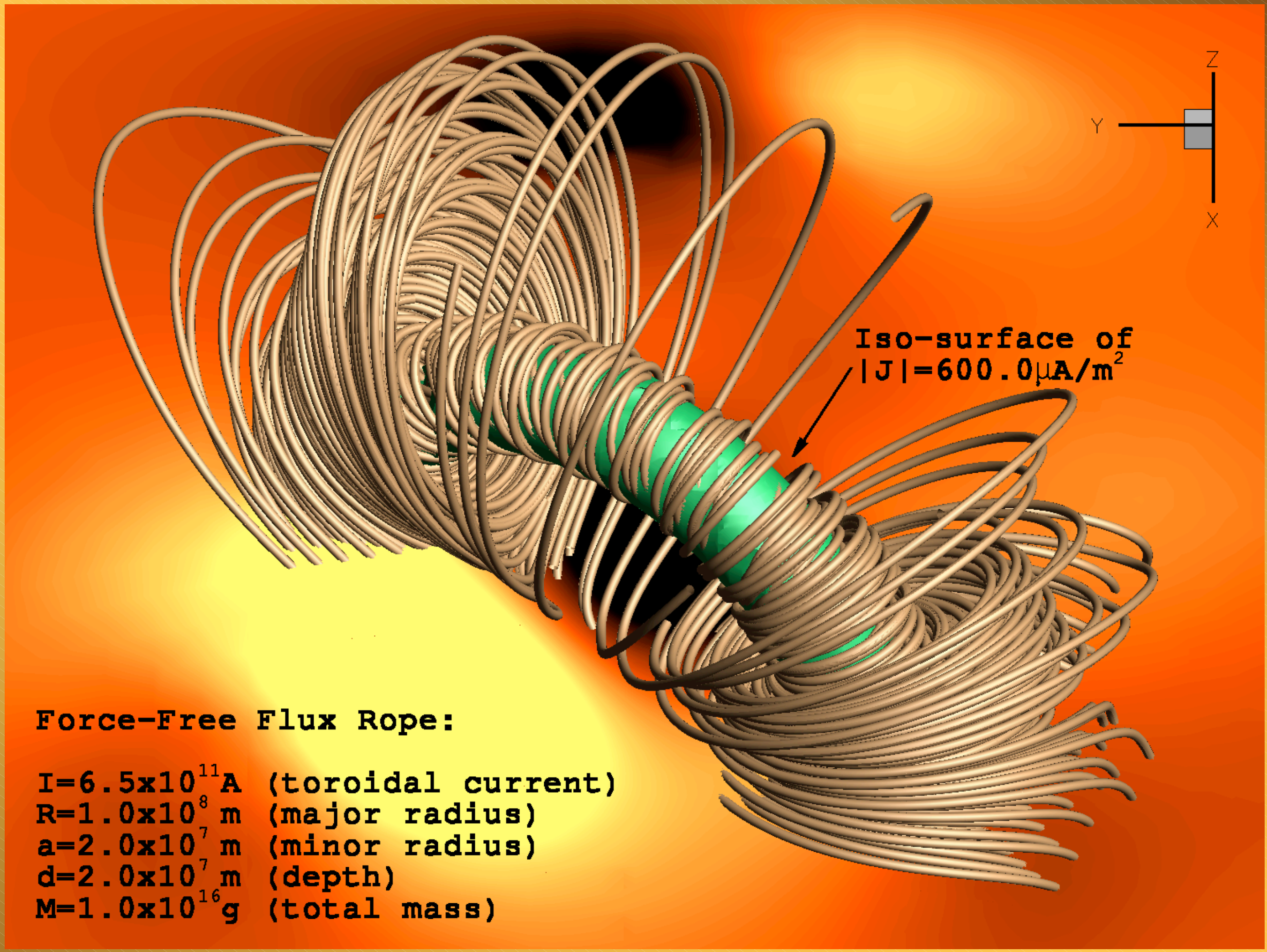


AR10488, Oct 28 ,2003 at 9:35 UT.

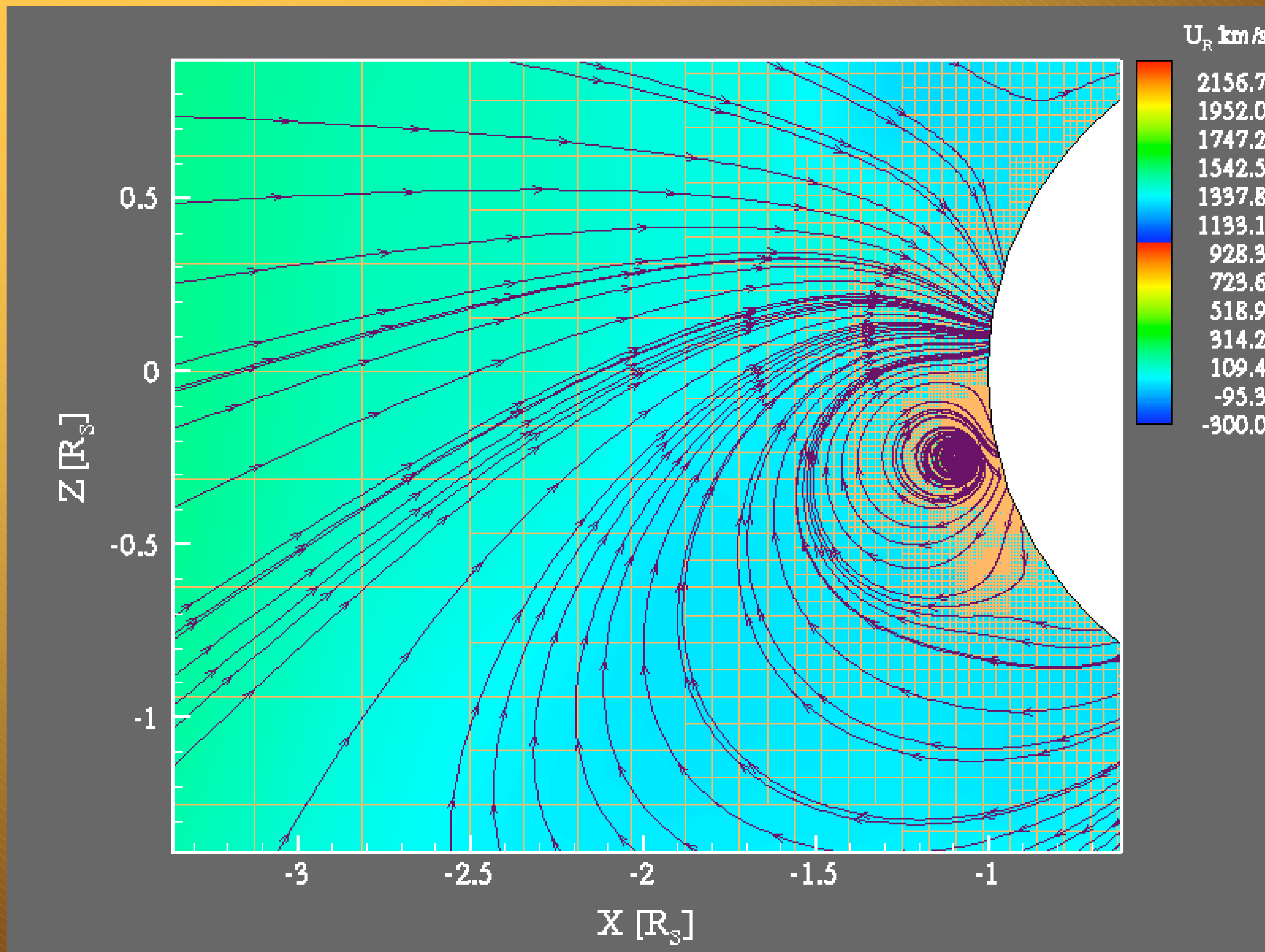
CME Propagation Model. (We Superimpose a Current Loop to Initiate a CME)

Image shows the superposition of a 3D force-free flux rope (Titov & Démoulin type) onto the background field taken from observations.

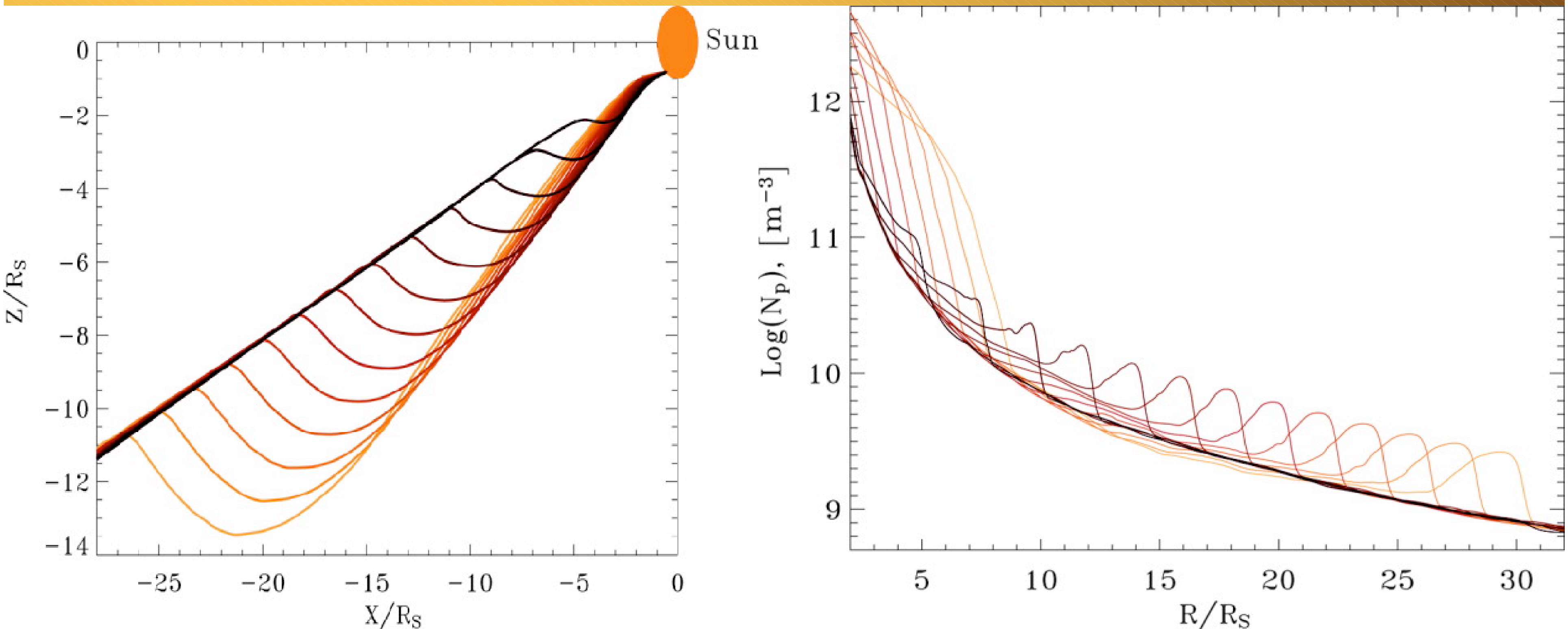
Flux rope in the ambient magnetic field is out of equilibrium (due to imbalanced hoop force) and it erupts, yielding the observed CME kinematics in the solar corona.



Dynamics of CME Eruption

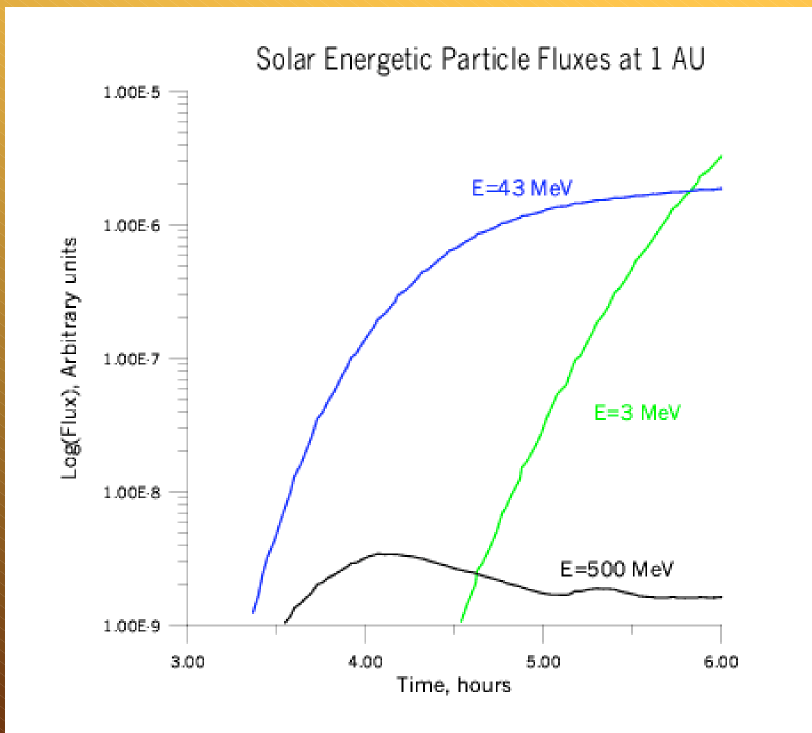


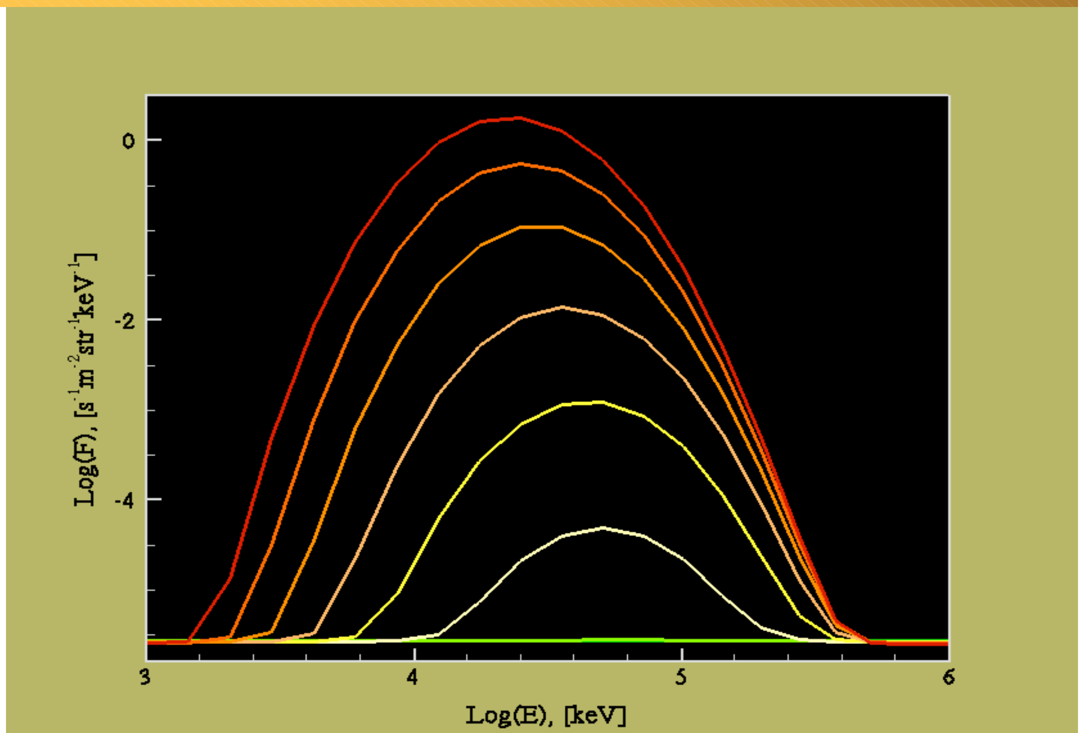
We Advance the Lagrangian Meshes Along the Moving Magnetic field Line and Extract the Plasma Dynamic Profiles



SEP Acceleration.

We extract the MHD parameters along the moving magnetic field line and integrate quasi-1D kinetic equation. Left figure - the University of Arizona model, right figure - the solution of the Parker equation





Monte-Carlo Approach for SEP Propagation

In collaboration with V. Tenishev, M. Combi

- The Monte-Carlo is used to describe the particle transport, from the shock wave towards the Earth, the spectrum of accelerated particles obtained as described above is used in sampling the particles
- We follow the sample particle trajectories (=integrate the kinetic equation along the phase trajectories of particles), using the same approximation as in the kinetic equation. At smaller radial distances (as long as the Larmour radius for protons is very small) the characteristic variables are the energy and the pitch-angle, at larger distances the effects of the finite Larmour radius should be resolved and full 3D equations of the particle motion in 3D magnetic and electric fields may be involved
- Scattering within the Monte-Carlo approach is a random process with the following probability to pass the distance of h without scattering:

$$p\left(h\right)=e^{-h/\lambda_P}, \text{where: } \frac{\lambda_P}{10^6\,km}=8.30\frac{\left(B/B_0\right)^2}{\delta B_x^2/\delta B_{x_0}^2}\left(\frac{l}{l_0}\right)^{2/3}\left(\frac{p/M_n c}{B/B_0}\right)^{1/3}\left(1+C\right)$$

- In scattering, the transversal diffusion should be taken into account, as a random displacement perpendicular to the magnetic field. It should be not the Larmor radius, but rather a correlation scale (see D.Ruffolo's poster

Sample the Particle Momentum and Follow its Trajectory

- Standard scheme: the energy distribution of test particles is proportional to that for the physical particles

$$\int_{p_{\mathrm{inj}}}^{p_i} f_{sw}\left(r\left(t_i\right), p, t_i\right) p^2 dp = \xi_2 \int_{p_{\mathrm{inj}}}^{p_{\max}} f_{sw}\left(r\left(t_i\right), p, t_i\right) p^2 dp$$

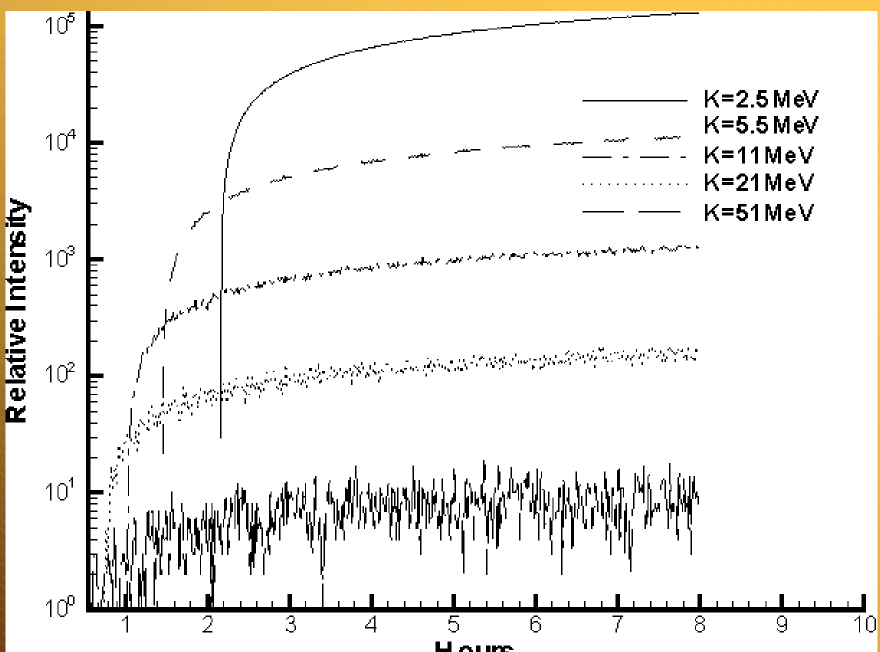
- The standard scheme works bad: the high energy particles are underrepresented. Use (statistical) weight function:

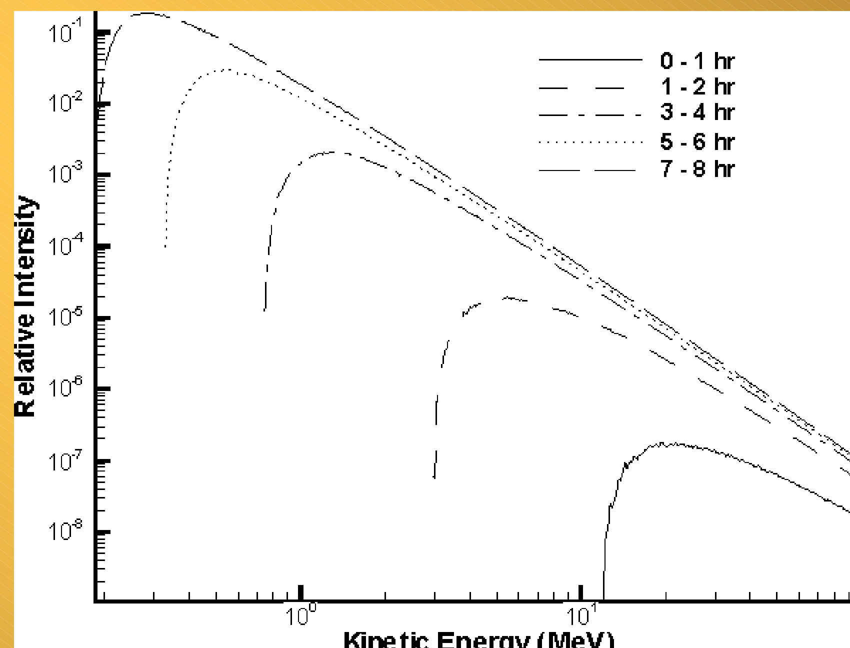
$$\ln E \in \left(\ln E\left(p_{inj}\right), \ln E\left(p_{\max}\right)\right)$$

$$w = f_{sw}\left(r, p\left(\ln E\right), t\right) p^2 (\ln E) \frac{dp(\ln E)}{d(\ln E)}$$

SEP Propagation Toward the Earth. Monte-Carlo Simulations

Fluxes near the Earth, for May,2,1998 event. Left figure: standard approach, the right one (no noise!) with the statistical weight





Computational Technologies

- High-resolution MHD simulation at several adaptive block grids.
- SWMF coupling toolkit (Sokolov, 2003). This is a multi-purpose software which particularly can be used for tracing the Lagrangian meshes along particular magnetic field line, interpolation, coordinate/unit transformations and data exchange between the models. NONE of these tasks is done in models: MHD models solve MHD equations (and does not do anything else), SEP model solves the kinetic equation (and does not do anything else).
- We achieve the codes integrity without loosing their identities

Summary of Results and Future Work.

Summary of Results:

- We incorporated magnetic data from MDI into a global MHD model of the solar corona, and use the dynamical results from CME simulation to drive the SEP acceleration and propagation models.
- We employ the FLAMPA technique to reduce the spatial dimensionality of the kinetic equation and solve it numerically to study the particle acceleration in realistic magnetic fields. The use of the gyrotropic distribution function seems to be more advantageous.
- The particle propagation is considered using the Monte-Carlo approach, keeping the possibility to take the perpendicular diffusion into account.

Future work:

- We are going to incorporate the Alfven turbulence model, by reducing the dimensionality of the transport equation for the waves in the same manner as we do it for kinetic equation.
- The observations for supra-thermal ions at 1 AU and for the level of turbulence will be used to integrate the kinetic equations backward in time and find the seed level of turbulence as well as the injection efficiency at the shock wave front
- This should make the model free from the absurd assumptions I like to make.

We Have These Data, but do not use