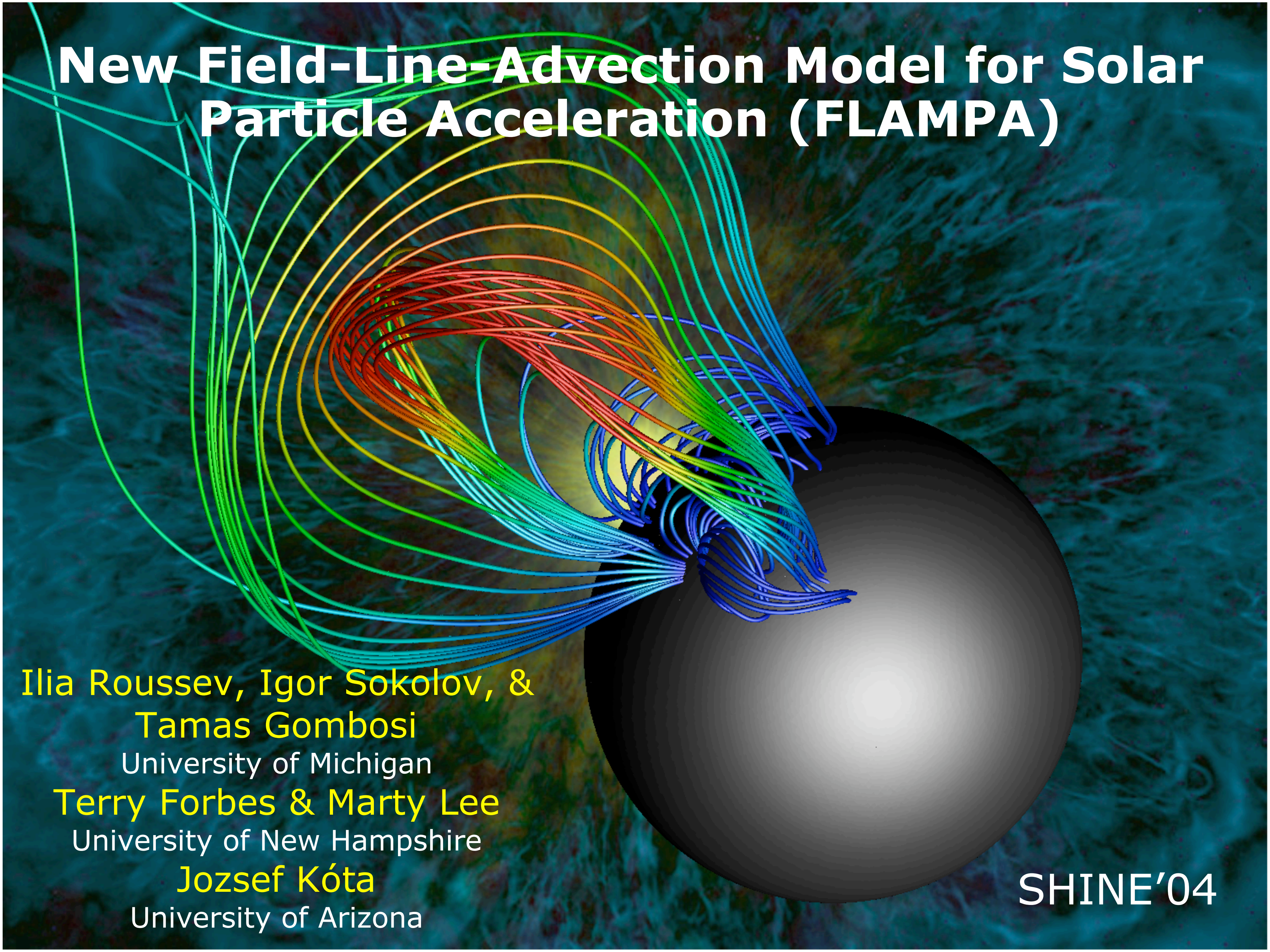
New Field-Line-Advection Model for Solar Particle Acceleration (FLAMPA)



Ilia Roussev, Igor Sokolov, & Tamas Gombosi
University of Michigan
Terry Forbes & Marty Lee
University of New Hampshire
Jozsef Kóta
University of Arizona

SHINE'04

Numerical Model of CME & Results

(from Roussev et al. 2004, ApJ, 605)

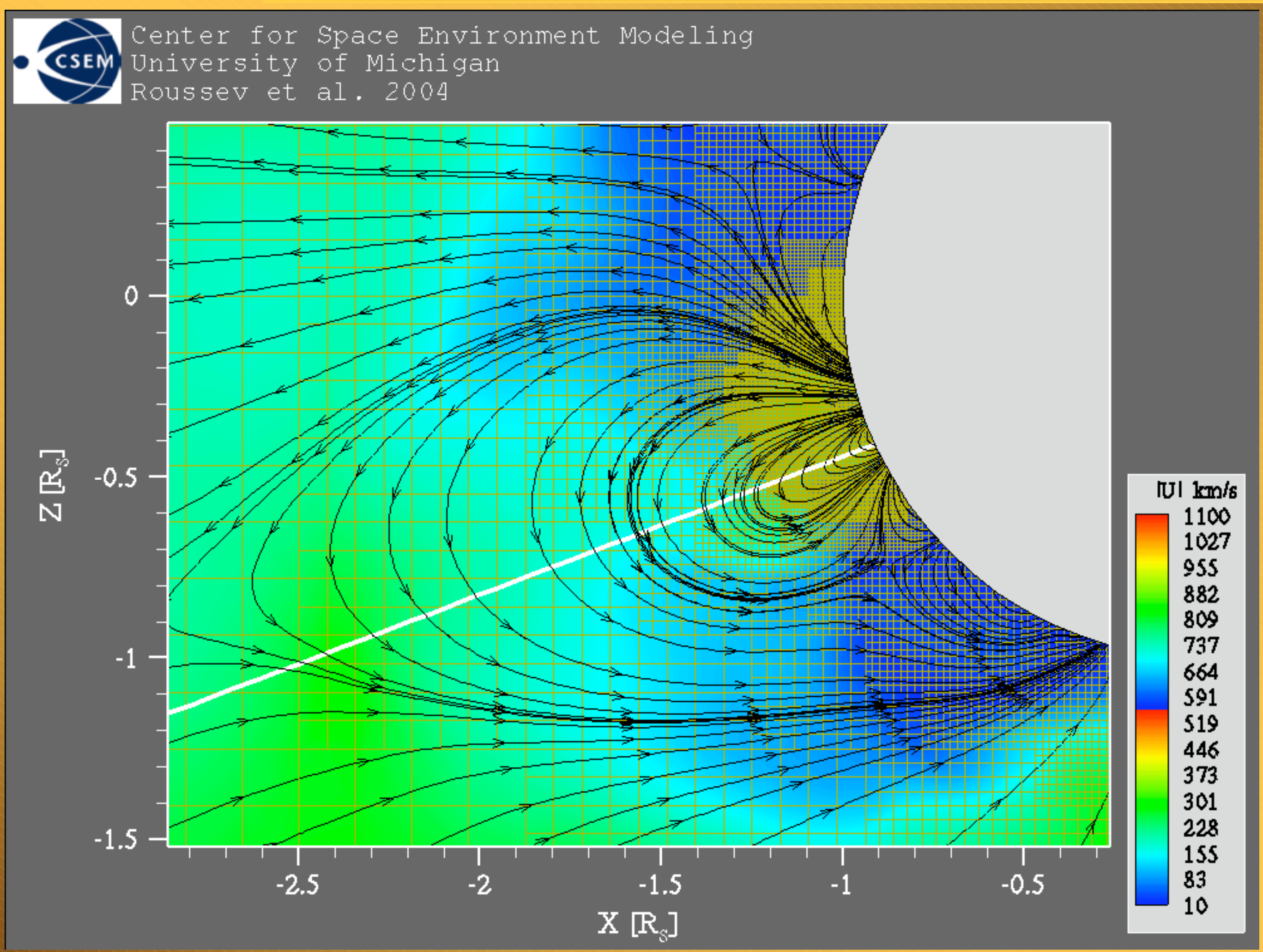
CME Initiation:

- Our model incorporates magnetogram data from Wilcox Solar Observatory and loss-of-equilibrium mechanism to initiate solar eruption.
- Eruption is achieved by slowly evolving boundary conditions for magnetic field to account for:
  - Sunspot rotation; and
  - Flux cancellation.

Results:

- Excess magnetic energy built in sheared field prior to eruption is 1.311×10^{31} ergs;
- Flux rope ejected during eruption achieves maximum speed in excess of 1,000 km/s;
- CME-driven shock reaches compression ratio of about 3 at distance of $4R_S$ from solar surface.

Dynamics of Solar Eruption



Description of FLAMPA

- We start from diffusion equation for cosmic rays:

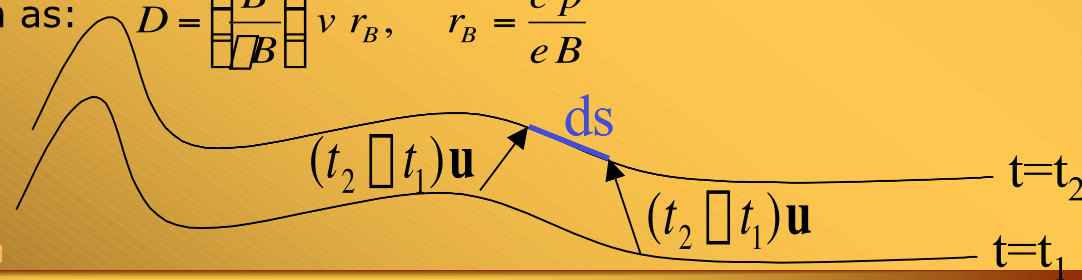
$$\frac{\partial f}{\partial t} + (\mathbf{u}\cdot\nabla)f - \frac{1}{3}(\nabla\cdot\mathbf{u})\frac{\partial f}{\partial \ln p} = \nabla\cdot(\mathbf{D}\cdot\nabla f)$$

(here *f* is the isotropic distribution function of particles)

- Assume spatial diffusion only along given field line: $\mathbf{D} = D\mathbf{b}\mathbf{b}, \quad \mathbf{b} = \mathbf{B}/|\mathbf{B}|$
- Use Lagrangian coordinates and assume that magnetic field is ideally frozen into plasma <=> we dictate that given magnetic field line consists of same Lagrangian meshes at any instant of time! Using the Lagrangian time derivative: $d/dt = \partial/\partial t + \mathbf{u}\cdot\nabla$ and employing $(\nabla\cdot\mathbf{B}) = 0, \quad (\nabla\cdot\mathbf{u}) = -d\ln\rho/dt$, we can reduce the CR diffusion equation, without any loss of generality, to ONE-DIMENSIONAL equation:

$$\frac{df}{dt} + \frac{1}{3}\frac{d\ln\rho}{dt}\frac{\partial f}{\partial \ln p} = |\mathbf{B}|\frac{\partial}{\partial s}\left[\frac{D}{|\mathbf{B}|}\frac{\partial f}{\partial s}\right]$$

- Diffusion coefficient is chosen as: $D = \left(\frac{B}{\delta B}\right)^2 v\, r_B, \quad r_B = \frac{c\,p}{e\,B}$



Coupling Between MHD Code and FLAMPA

- We trace given field line by following the Lagrangian meshes (*N*~1500) it consists of. We solve *N* time equations of the kind:

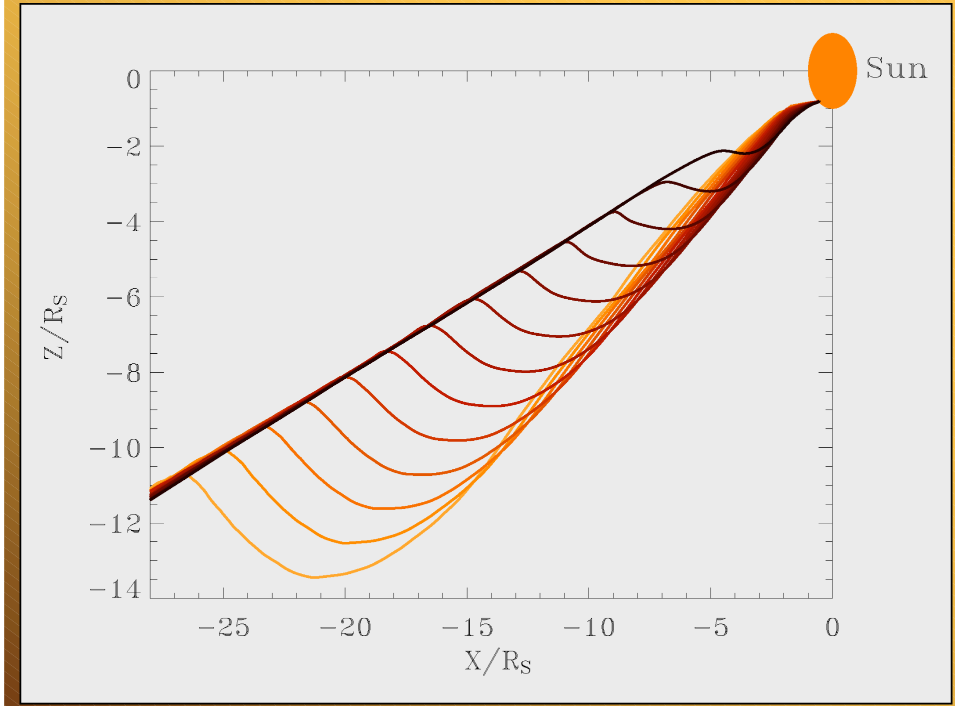
$$\frac{d\mathbf{x}_n}{dt} = \mathbf{u}(\mathbf{x}_n, t)$$

  with velocity field **u** taken from MHD numerical solution, once every time step.
- After previous coupling at time t_1 we allow shock wave to pass distance *ds* between two neighboring Lagrangian meshes and at this time t_2 we do next coupling between MHD code and FLAMPA. To do this, we extract values of |**B**|, temperature *T*, and density ρ along traced field line and then send these to SEP code.
- We update particle distribution function, *f*, from time t_1 to t_2 using the following discretization:
  - $\frac{\partial f}{\partial \ln p}$ as advection with respect to momentum coordinate, using an explicit upwind scheme of 2nd order of accuracy;
  - $\frac{\partial}{\partial s}\left(\frac{D}{|\mathbf{B}|}\frac{\partial f}{\partial s}\right)$ as diffusion along spatial coordinate, using an implicit scheme.
  - Boundary condition at injection energy is:
    (we assume E^{-1} spectrum for suprathermal particles)

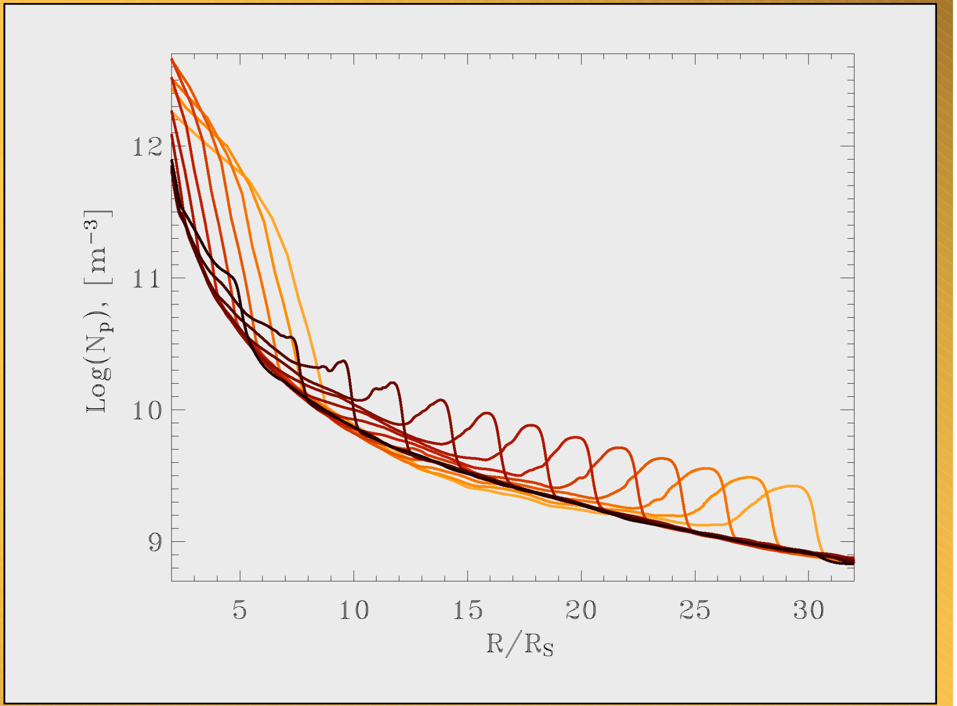
$$f\,|_{p=p_{Inj}} = \frac{1}{4\pi}\frac{N}{(2m_p T)^{3/2}}\left(\frac{\sqrt{2m_p T}}{p_{Inj}}\right)^4$$

Time Evolution of Field Line and Number Density

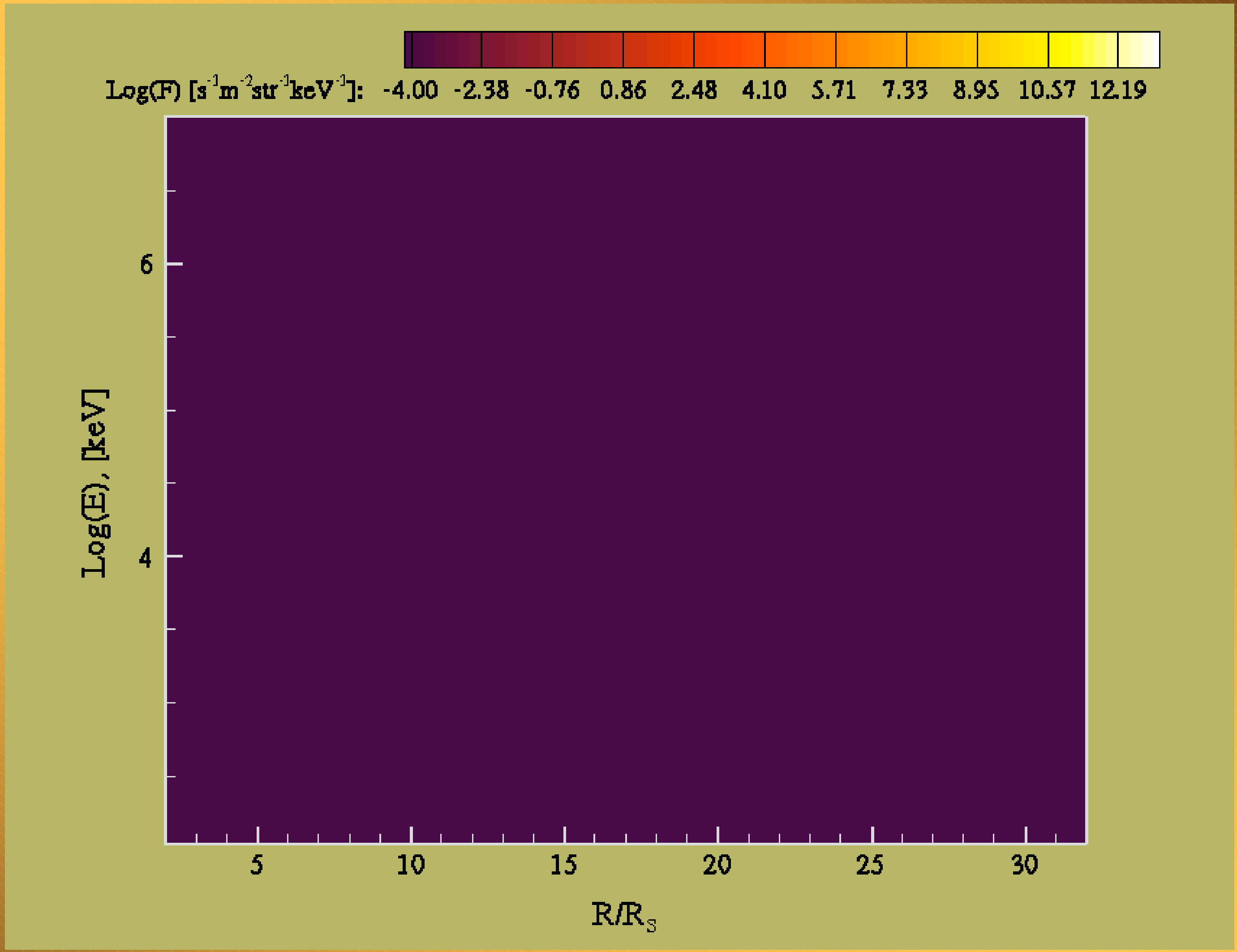
Field line position (in XZ-plane) at 13 instants of time (30 min apart)



Number density distribution along same field line at same 13 instants



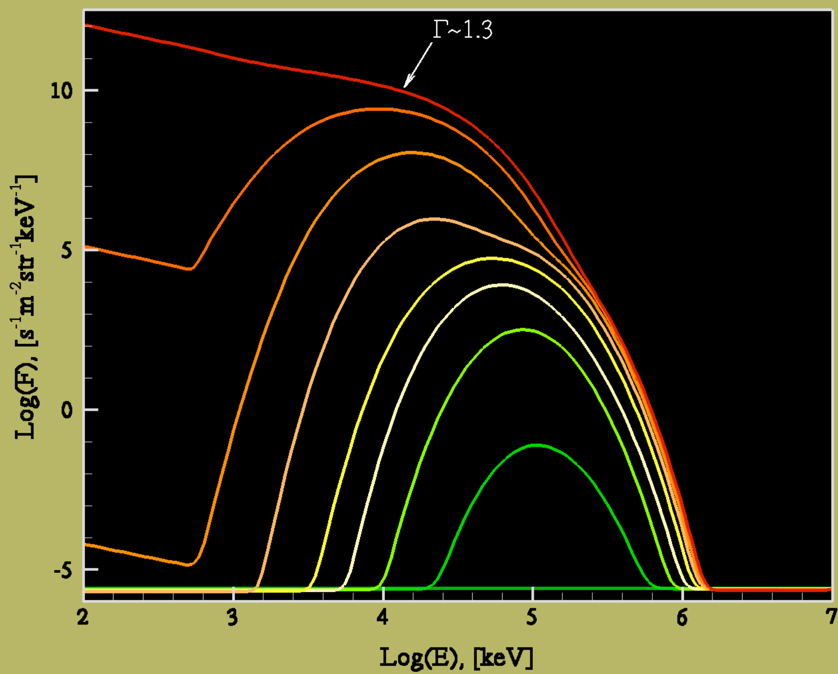
Time Evolution of DPI



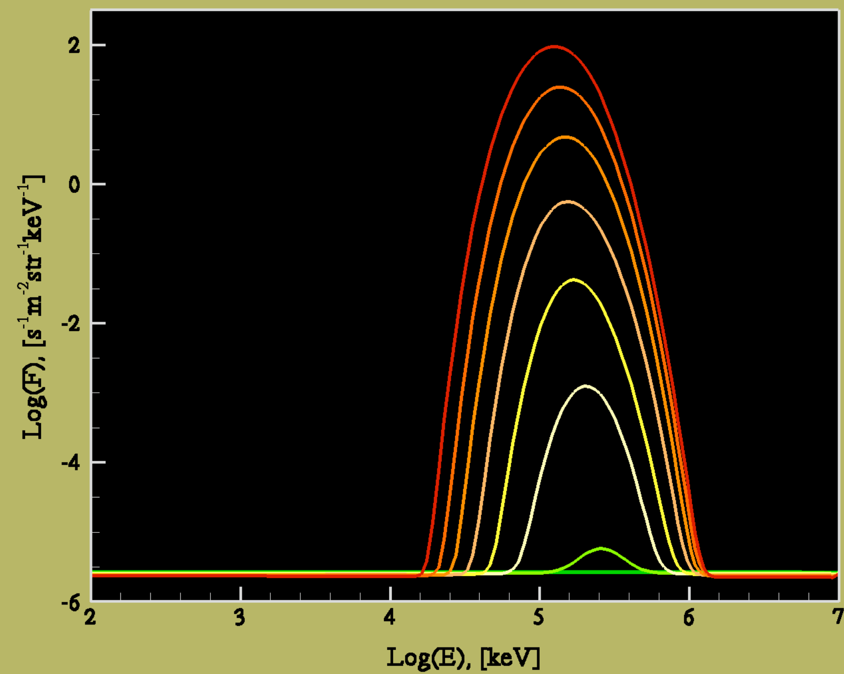
- Differential particle intensity, *F (r, E)*, shown as function of time (over 6.0 hrs).
- Shock wave traced out to $31R_S$.
- High-energy particles escape upstream of the shock wave — precursors of space weather storm.

Particle Spectra: Time Sequence at Two Radial Locations

R=12R_S (before and after shock wave passes)



R=30R_S (upstream of shock wave)



Time interval between two adjacent curves is 10 min. Dark red curve corresponds to t = 1.6 hrs (shock at R=12.2R_S), whereas low-lying dark green curve refers to t = 0.27 hrs.

Summary of Results

FLAMPA:

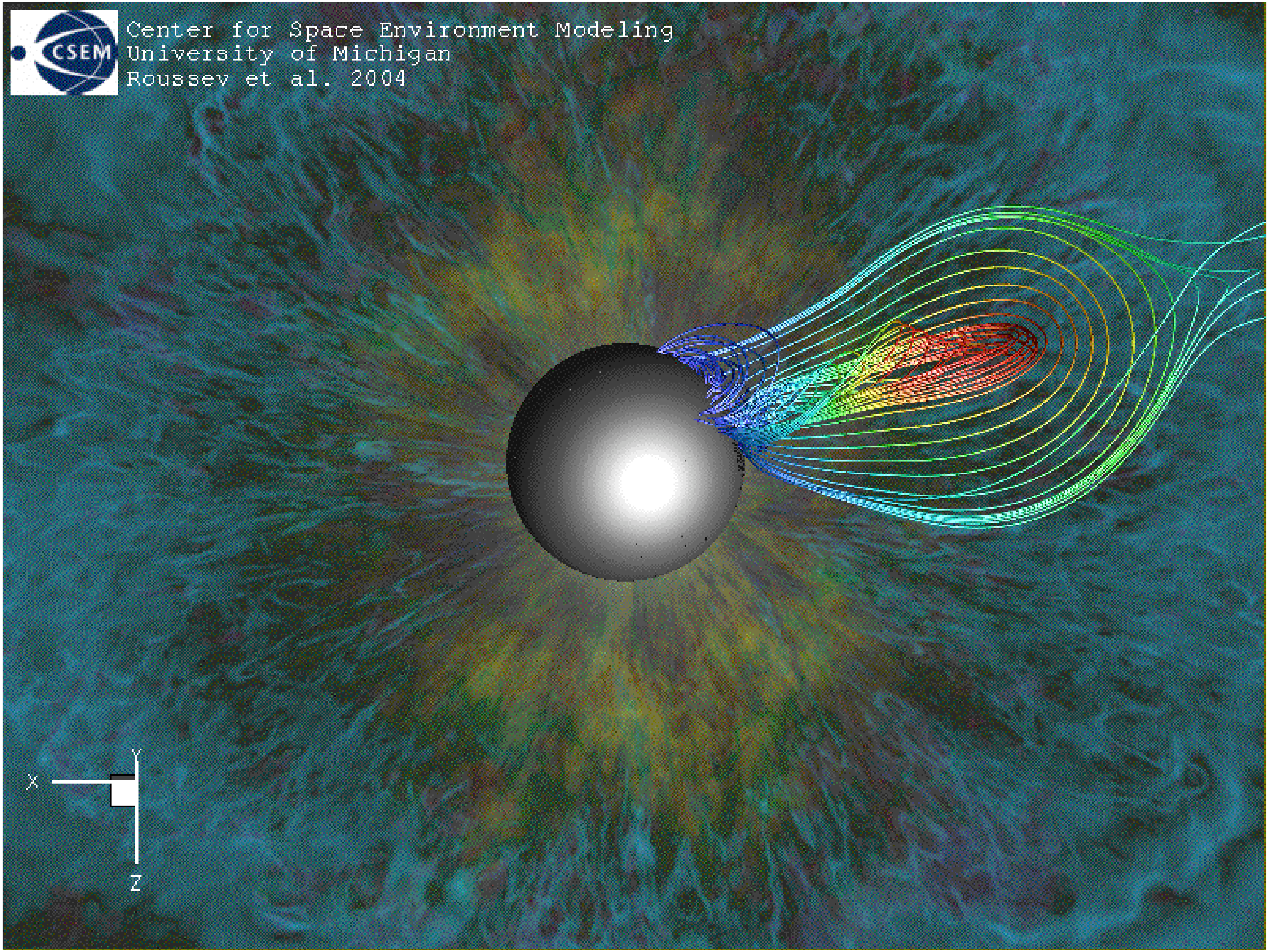
- Our model includes all important effects for SEP acceleration at CME-driven shock waves and employs Lagrangian meshes.

Results:

- We followed dynamical evolution of solar protons and demonstrated acceleration up to ~ 1.7GeV by realistic CME-driven shock wave;
- We performed frequent dynamical coupling between two realistic numerical models in order to take into account full time-dependent history of evolving shock wave;

Future:

- Follow dynamics of energetic particle distribution out to 1AU and compare with observed SEP fluxes;
- Perform simulations for repetitive solar eruptions - Halloween Storms of 2003 are good start!



Center for Space Environment Modeling
University of Michigan
Roussev et al. 2004
CSEM
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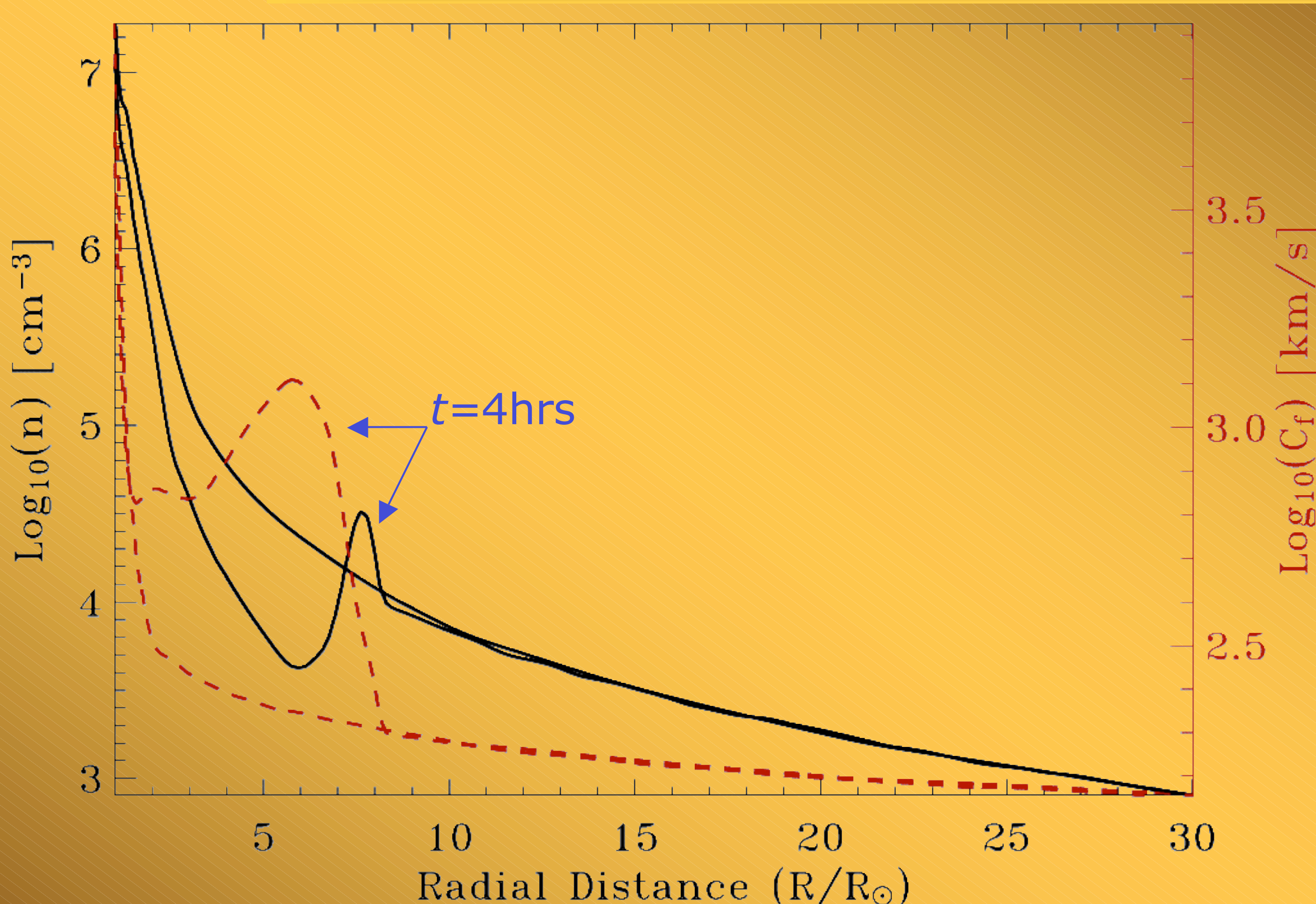
Conclusions

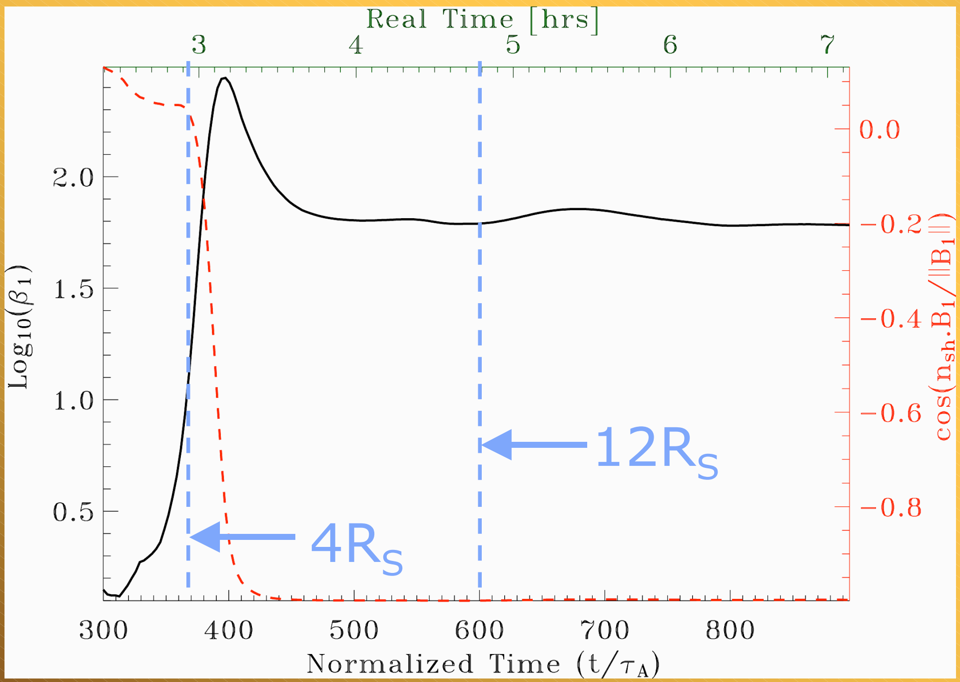
- CME-driven shock can develop close to Sun sufficiently strong to account for energetic solar protons up to a few GeV!
- SEP acceleration by diffuse-shock-acceleration mechanism, up to energies sufficient for penetrating into spacecraft, occurs in Sun's proximity at R~(4-13)R_S and has relatively short time scale (~2 hrs).

Dynamic Profiles of Plasma Density and Fast-wave Speed

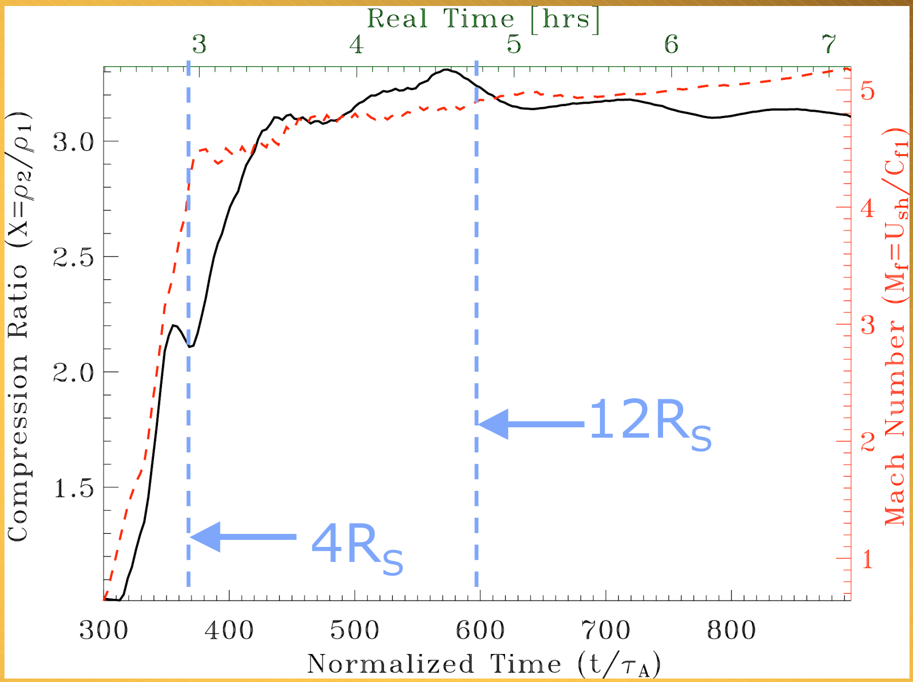


Curves of number density and fast-wave speed (red curves) as derived along white line at t=0 and t=4hrs.

Shock Evolution Cont.



Plasma beta (log-scale) and cosine of angle of upstream field to shock normal against time.



Shock compression ratio and fast-wave Mach number against time.