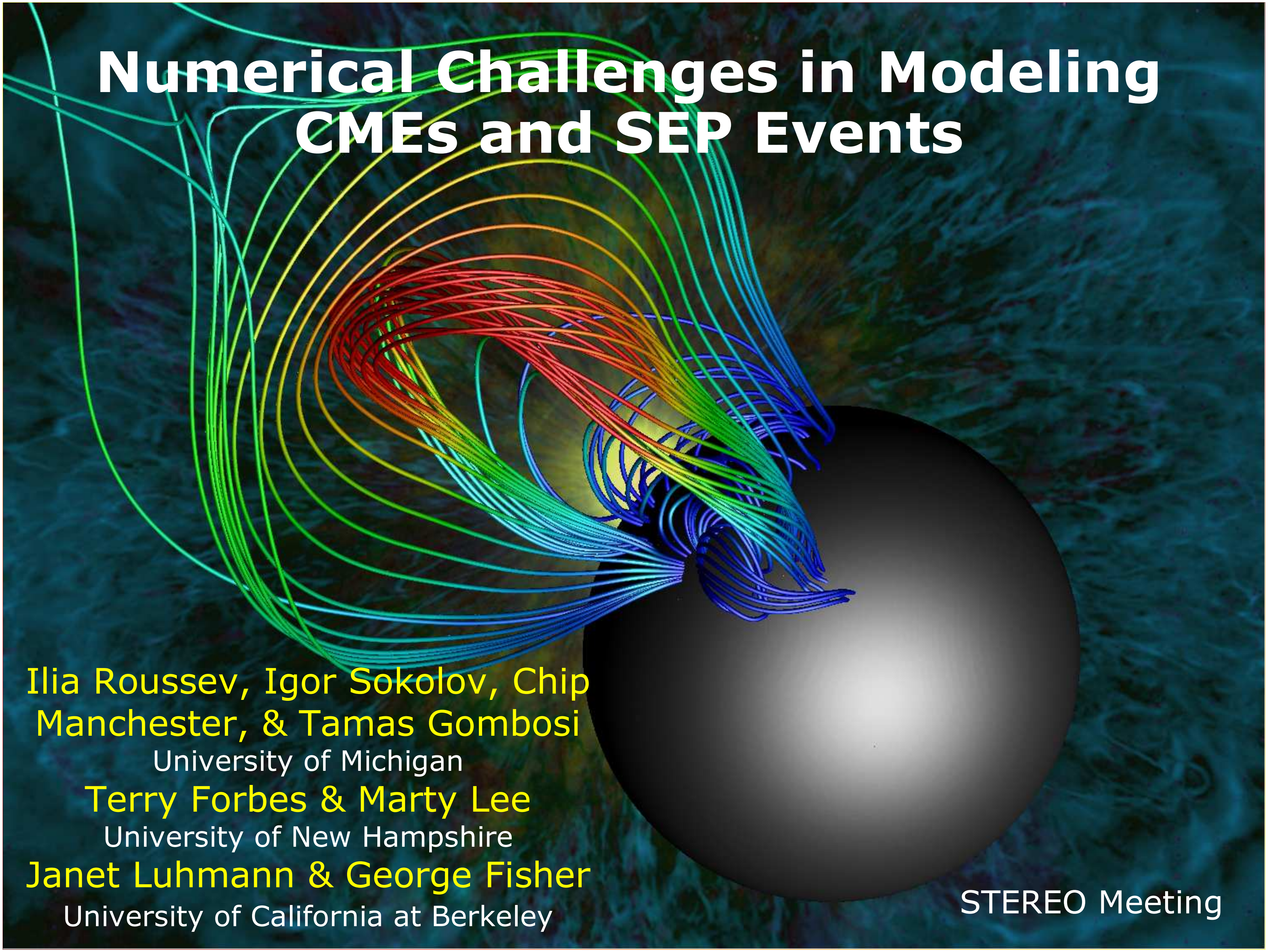
Numerical Challenges in Modeling CMEs and SEP Events



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STEREO Meeting

Research at CSEM: Scientific Objectives

- Understand physical causes of CME initiation (Roussev *et al.* 2003, ApJ, 588, L45; Roussev *et al.* 2004, ApJ, 605, L00; and more to come).
- Model propagation of CMEs in low corona and inner heliosphere (Manchester *et al.* 2004, JGR, 109, A01102; Manchester *et al.* 2004, JGR, 109, A02107).
- Explore mechanisms of SEP acceleration in low corona and interplanetary medium (Roussev *et al.* 2004, ApJ, 605, L00; we are just starting).
- Develop fully three-dimensional, time-dependent model of magnetic topology, thermodynamic state, & velocity structure of ambient solar wind (Roussev *et al.* 2003, ApJ, 595, L57; yet more to be done).
- Develop numerical models which incorporate real data and predict observable quantities (work in progress).
- Study variable conditions in space that can have adverse effects on human life and society; develop predictive space weather models (SWMF; work in progress).
- All of the above requires new realm of observations - **STEREO!**

Scientific Objectives of STEREO

STEREO will:

- Provide ideal opportunity to determine magnetic field geometry prior to solar eruptions - important for predictive space weather modeling;
- Observe erupting filaments and coronal structures in three-dimensions - important for testing and validating numerical models of solar eruptions;
- Provide more constraints to numerical models of CME initiation and evolution;
- Enable modelers to couple photospheric with coronal magnetic field measurements;
- Provide direct tests for SEP models;
- Observe complete propagation of solar transients from Sun to L1;
- Require a new level of coupling between numerical models and observations;

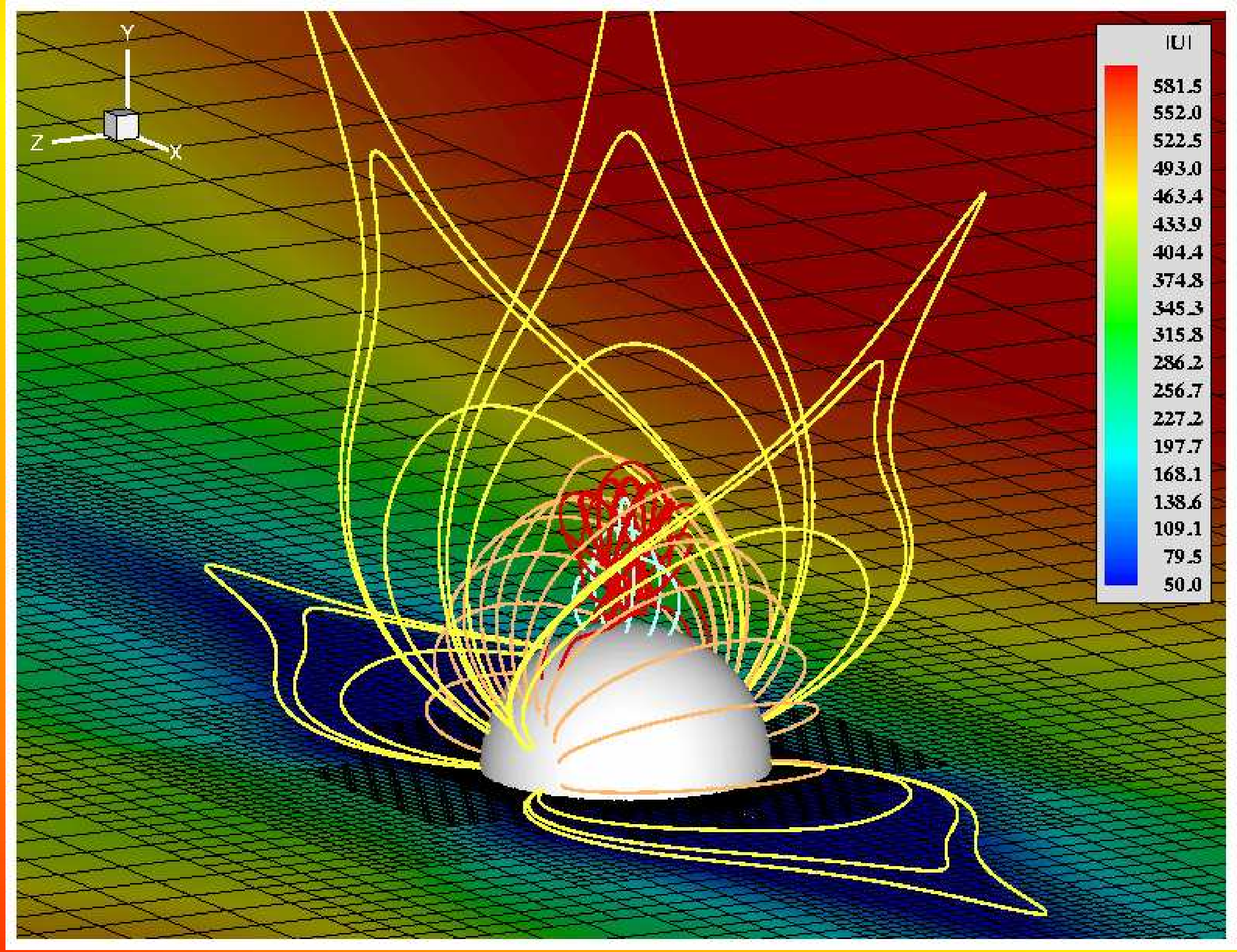
Ultimately, **STEREO** will help us better understand the coupling of scales in the complex Sun-Earth system!

Model of CME Propagation in Low Corona and Inner Heliosphere

(from 2xManchester *et al.* 2004)

3D View of Flux Rope for Initial State

Magnetic field lines are drawn as solid colored lines at *t*=0 hrs. The flux rope is drawn with blue and red lines, while orange and yellow lines show the poloidal field of the steady-state equatorial streamer belt. On the x-z plane, the computational mesh is drawn with black lines superimposed upon a false color image of the velocity magnitude.



Sun-to-Earth Simulation of CME Propagation

Color code represents the plasma temperature in meridional plane of the heliosphere. White lines visualize magnetic field lines. Grid structure is shown as the black mesh.

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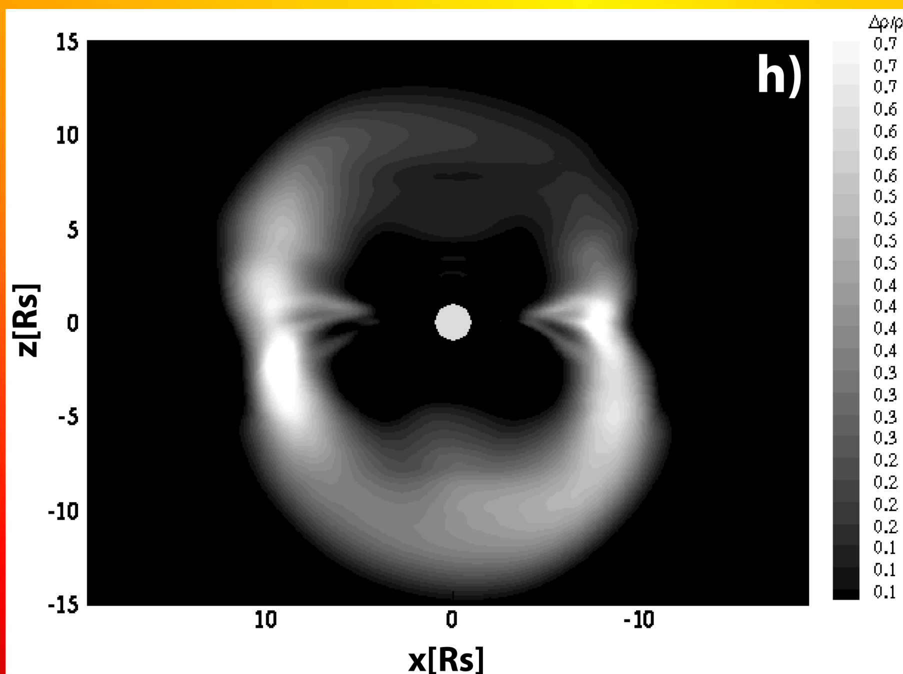
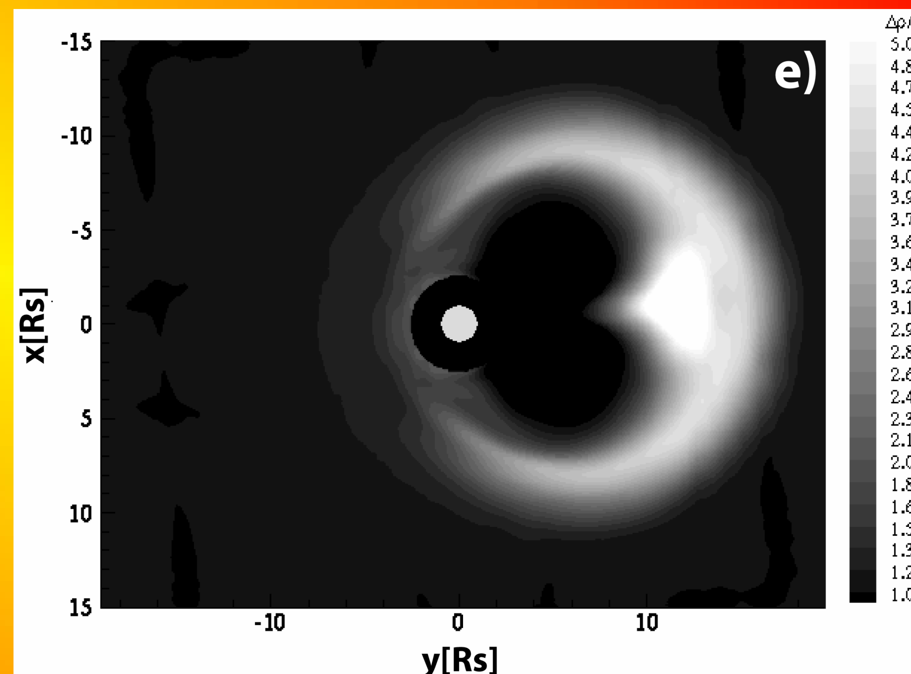
PNG decompressor
are needed to see this picture.

Views of Eruption in White Light at *t*=2 hrs.



View from L1



View from north pole

Features of CME Propagation Model

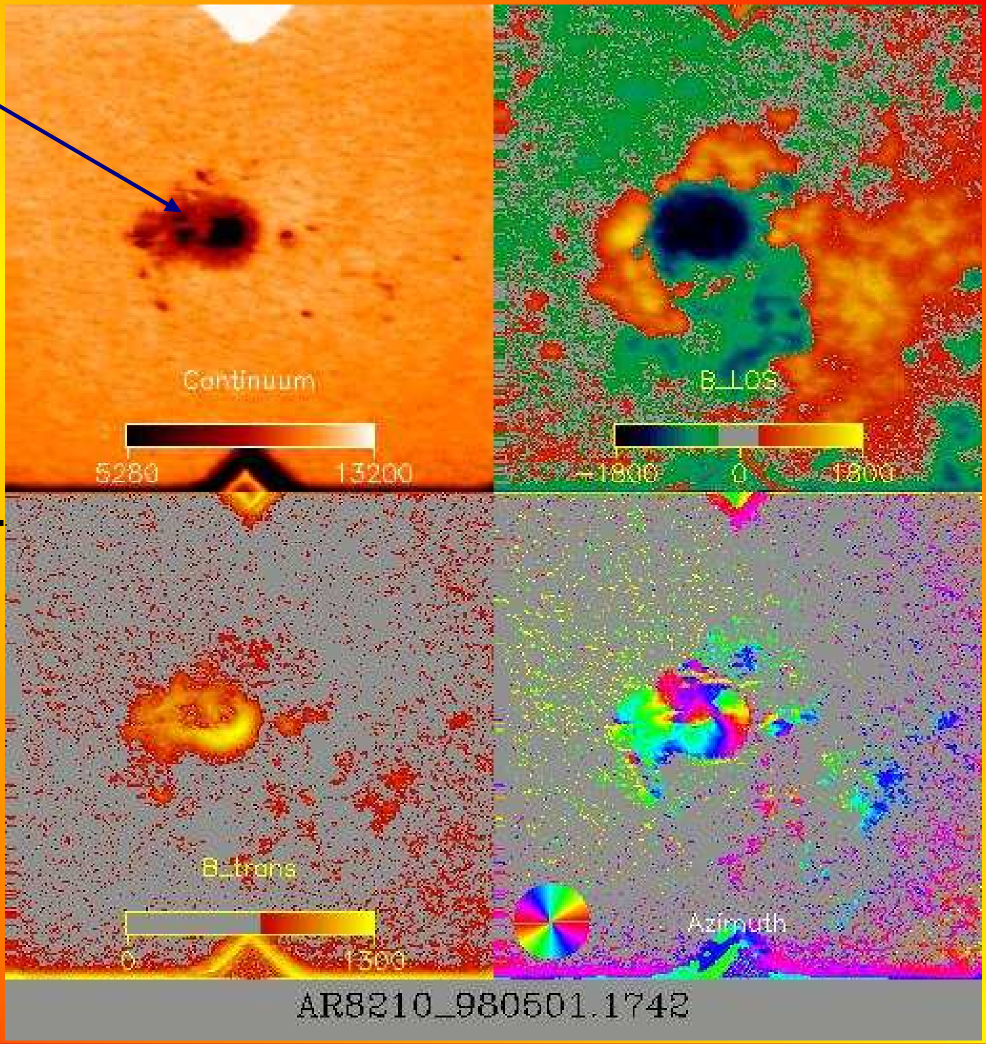
- 3D flux rope embedded in helmet steamer with three-part density structure.
- CME driven by initial force imbalance yields observed values for mass and kinetic energy.
- CME properties are:
  - Peak velocity > 1,000 km/s;
  - Flux rope mass ~ 1.0×10^{15} g;
  - Kinetic Energy ~ 4.0×10^{31} ergs;
- CME propagates to 1 AU with geoeffective properties.
- Shock formation and interaction with the bi-modal solar wind.
- SEP acceleration at the shock and post-shock compression:
  - Tracking magnetic field lines;
  - Resolving the shock along a particular field line.

Numerical Model of CME Initiation and Evolution Inspired by Observations of 1998 May 2 Event

(from Roussev *et al.* 2004)

Observations of Field Evolution

Field Structure of NOAA AR8210 on 1998 May 1 (IVM; Mees Observatory)



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PNG decompressor
are needed to see this picture.

MDI movie showing time-evolution of NOAA AR8210 from 30ºE to 30ºW (from Sam Coradetti)

Numerical Model

- We start with magnetic field obtained using Potential Field Source Surface Method.
- Spherical harmonic coefficients (n_{SHC}=29) are obtained from magnetogram data of Wilcox Solar Observatory. They are derived using Carrington maps for rotations 1935 and 1936.
- We use empirical model presented by Roussev *et al.* (2003, ApJ, 595, L57) to evolve MHD solution to steady-state solar wind, with helmet-type streamer belt around Sun.
- Once steady-state is achieved, we begin inducing transverse motions at solar surface localized to AR8210.
- These boundary motions resemble following observational facts:
  - Sunspot rotation; and
  - Magnetic flux cancellation.
- Numerical techniques similar to ours have been used in past to create flux ropes and initiate CMEs in idealized, bi-polar (Inhester *et al.* 1992; Amari *et al.* 1999, 2000, 2003), and multi-polar (Antiochos *et al.* 1999) type magnetic configurations;

Dynamics of Solar Eruption

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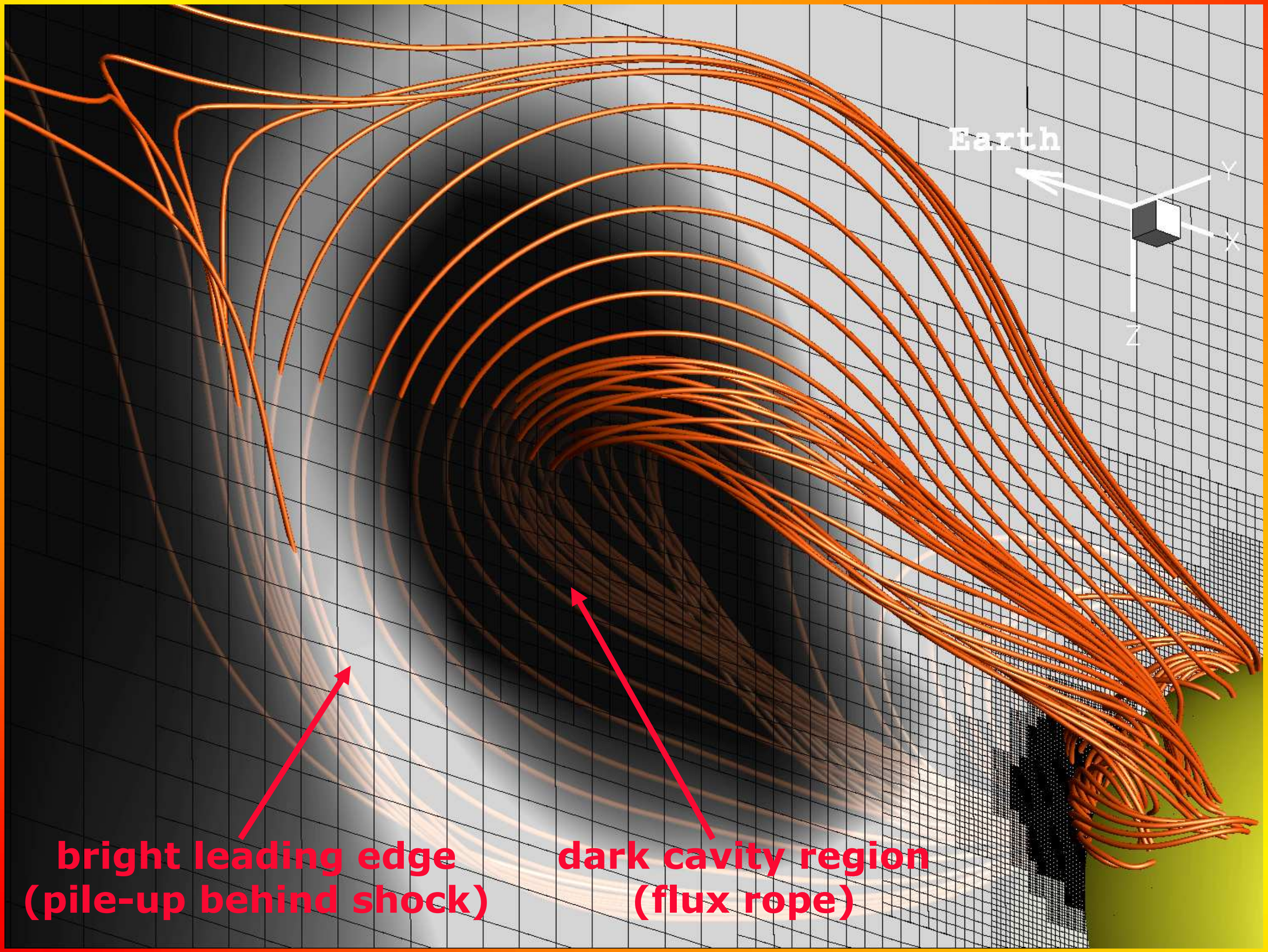
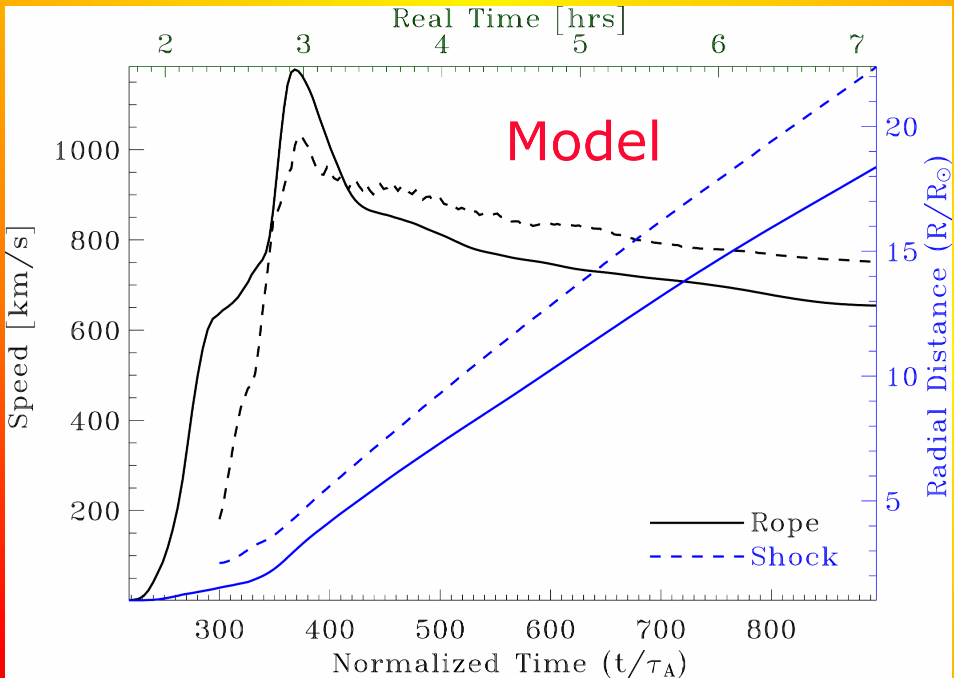
are needed to see this picture.

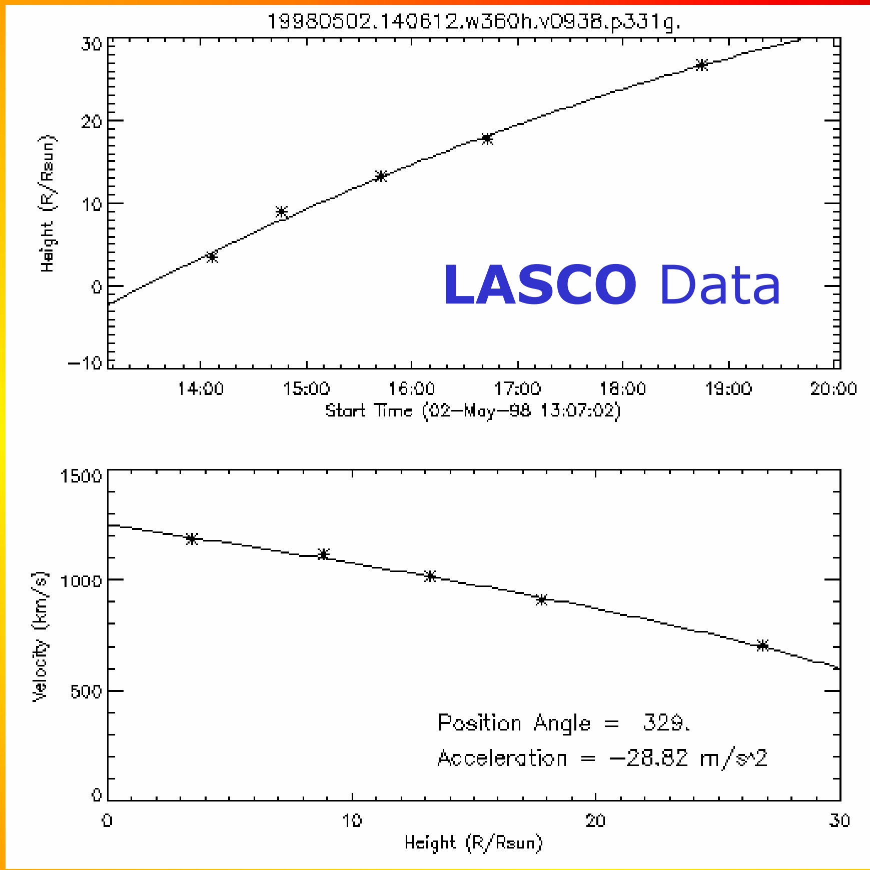
Density Structure & Field Geometry at *t*=3 hrs.



Trajectories & Speed Curves



Trajectory curves of flux rope and shock (blue curves) in plane *y*=0. Radial velocities of rope and shock are shown by corresponding black curves.

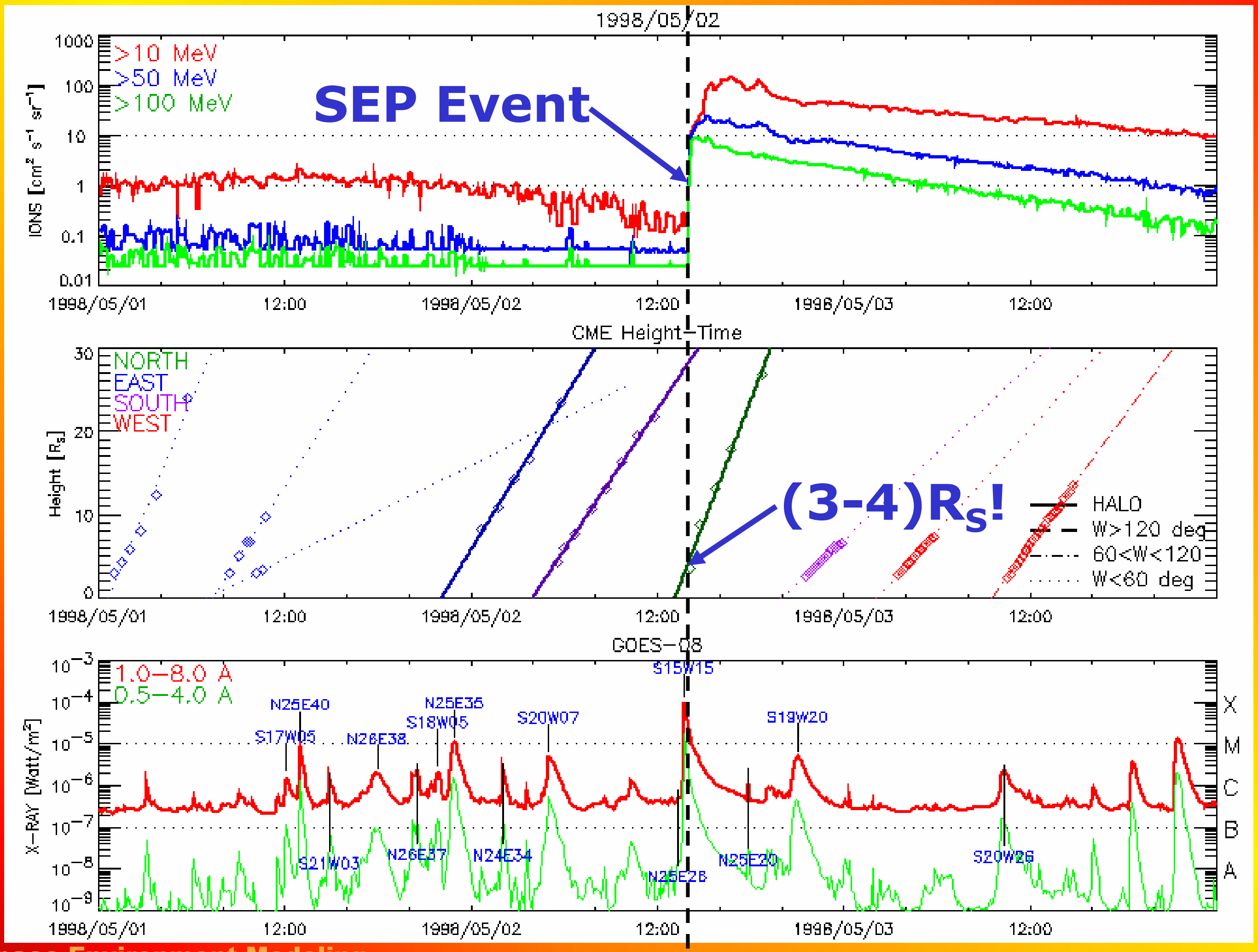


Deceleration:

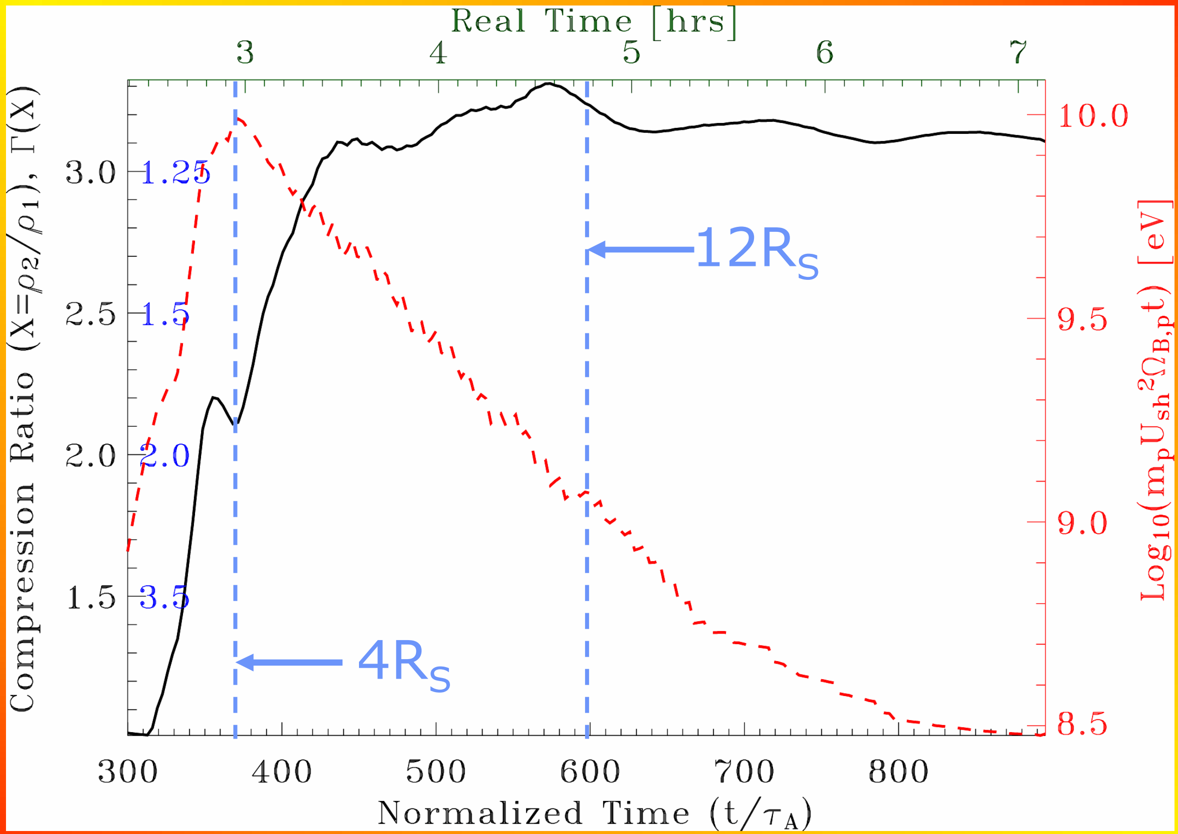
Observed 28.8 m/s^2

Model gives 18.1 m/s^2

SEP Data for 1998 May 2 Event



Shock Evolution



Compression ratio of shock and proton cut-off energy predicted by diffusive-shock-acceleration theory. Interior labels along left axis indicate spectral index for non-relativistic particle flux used in theory: $\Gamma=0.5(X+2)/(X-1)$. Lower values of Γ indicate harder spectrum

Summary of Results

Model:

- 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 emergence and subsequent 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 1,040 km/s;
- CME-driven shock reaches fast-mode Mach number in excess of 4 and compression ratio greater than 3 at distance of $4R_S$ from solar surface.

Conclusions

- CME-driven shock can develop close to Sun sufficiently strong to account for energetic solar protons up to 10 GeV!
- SEP acceleration by diffuse-shock-acceleration mechanism, up to energies sufficient for penetrating into spacecraft, occurs in low corona at R~(3-12)R_S and has relatively short time scale (~2 hrs.).
- To simulate this properly, high-resolution MHD simulation should be coupled with kinetic equation for SEP diffusion along magnetic field lines, including Fermi type-A acceleration. Magnetic field line(s) motion should be traced using Lagrangian coordinates.
- Physical requirements to numerical models of solar eruption:
  - Initial conditions should *not* produce shock wave as result of strong initial non-equilibrium;
  - However, solar eruption should be sufficiently energetic, rather violent, to form strong shock wave in Sun's proximity.

QuickTime™ and a
PNG decompressor
are needed to see this picture.

Flux Rope Model of Gibson & Low

- 3D self-similar CME model of Gibson & Low (1998, ApJ, 493):
  - Model has complex magnetic topology of spheromak-type flux rope distorted into 3D tear-drop shape;
  - Model possesses three-part density structure associated with CMEs including dense front, cavity, and dense core;
  - Magnetic field supports weight of prominence, thus free energy is stored in magnetic field of flux rope;
  - Entire flow is self-similar, characterized by radial outflow whose speed increases linearly with distance from origin;
  - No interaction of CME with background solar wind is present in analytical model.

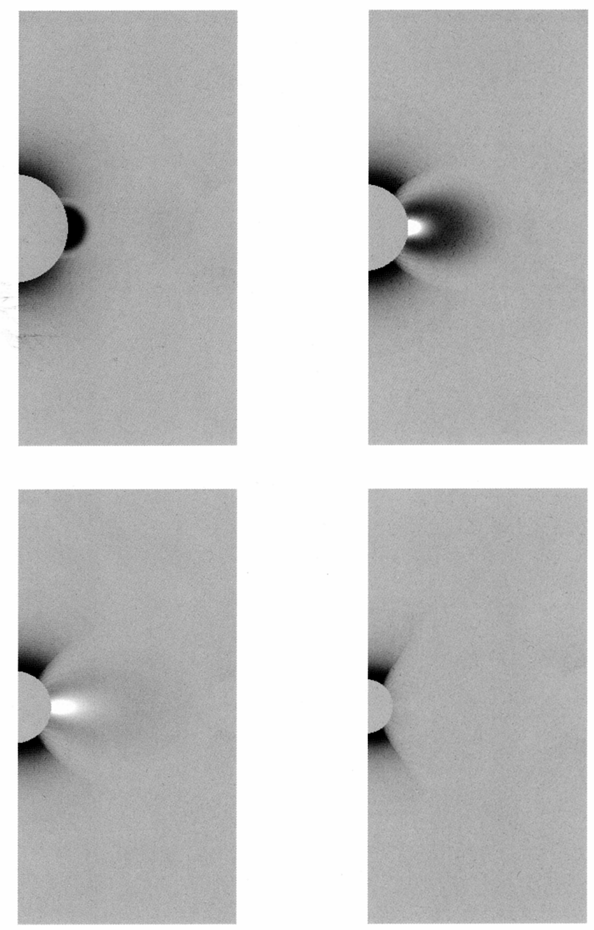
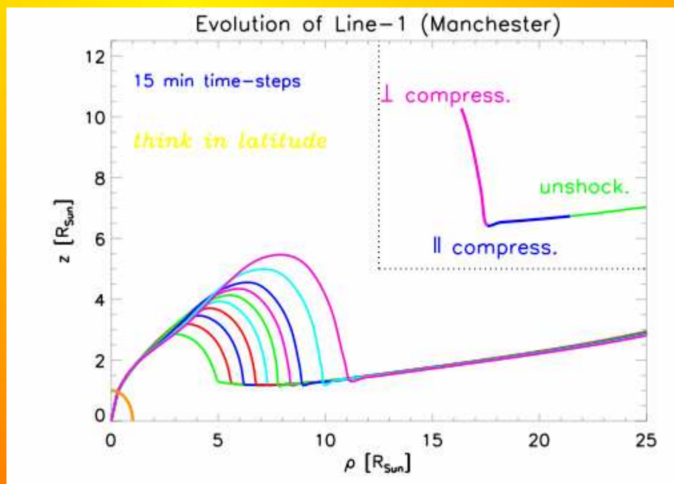
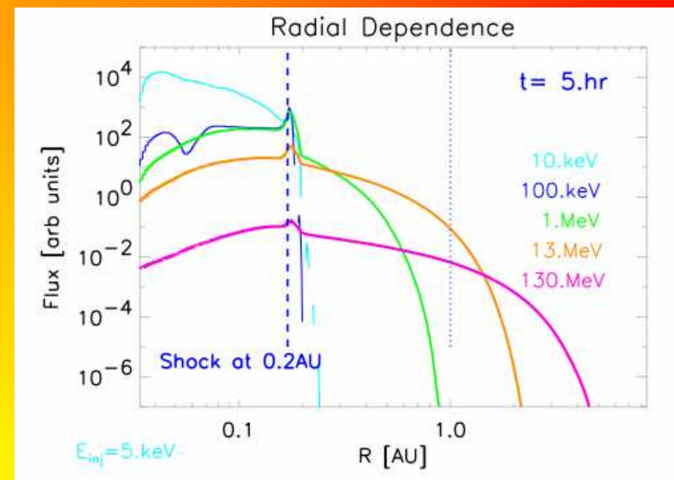
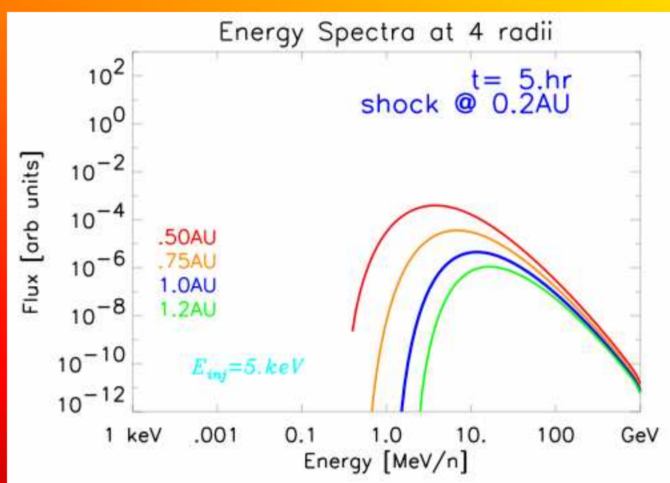


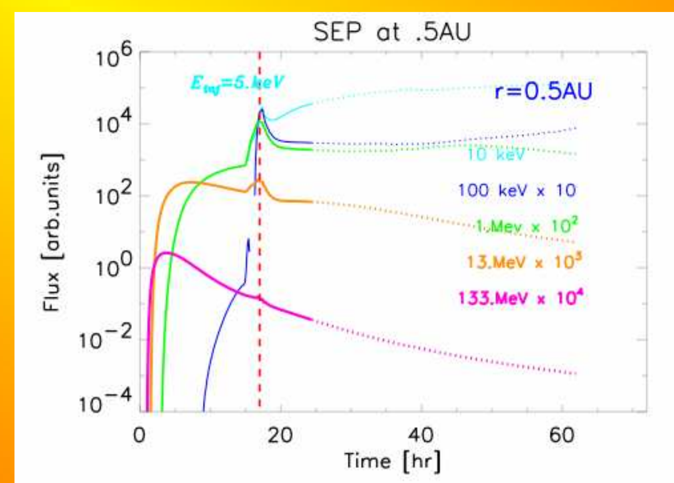
FIG. 9.—Self-similar evolution of CME solution for polarized brightness (PB), seen projected into the Y-Z plane. The bubble axis is seen oriented with $X' \parallel X$. Times correspond to the four time steps of Fig. 7.

Fermi Acceleration of SEPs at CME-Driven Shock





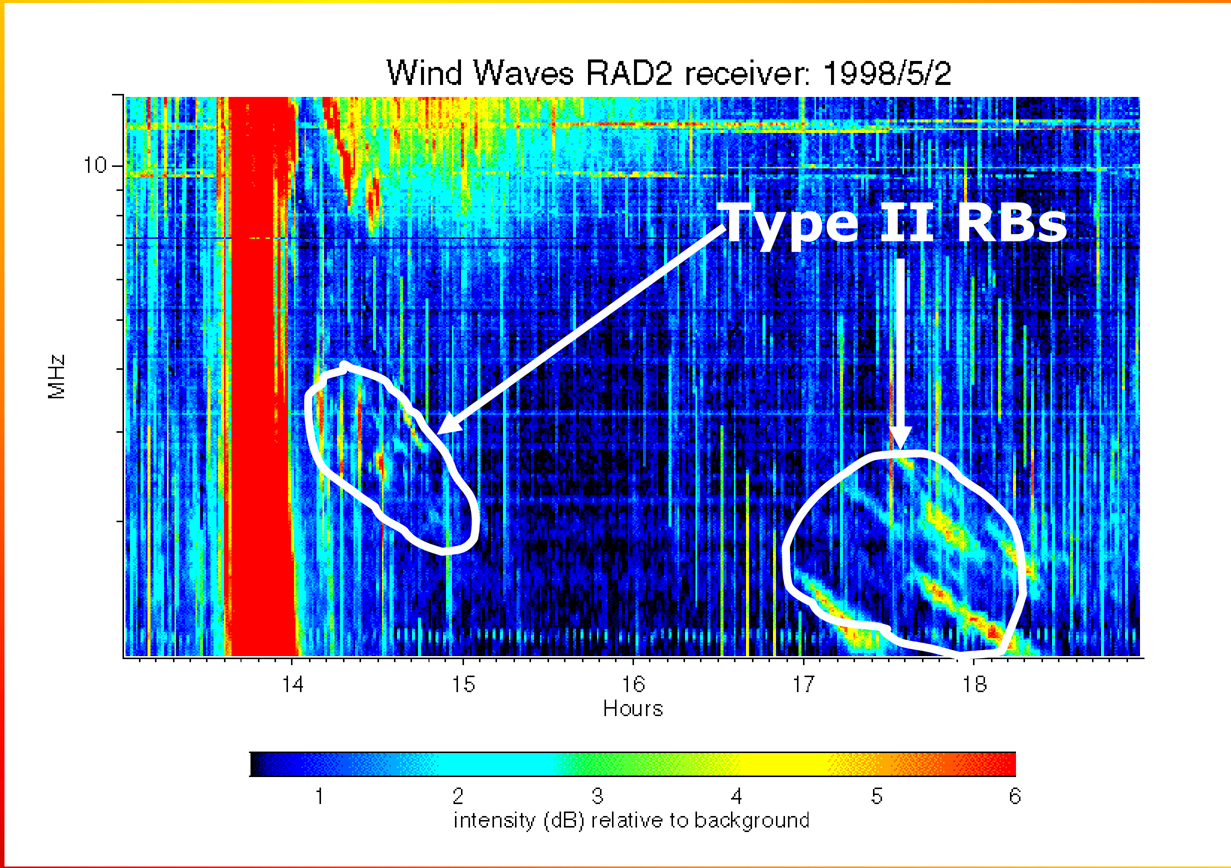




NOAA AR8210: Summary of Observations

- Series of intense flares and CMEs, including homologous events, occurred in NOAA AR8210 from April through May of 1998;
- CME event we consider took place on 1998 May 2 near disk center (S15^o,W15^o), and CME speed inferred from observations by LASCO was in excess of 1,040 km/s;
- X1.1/3B flare occurred in NOAA AR8210 at 13:42 UT, which was associated with SEP event observed by NOAA GOES-9 satellite. Ground-level event was observed by CLIMAX neutron monitor;
- Total magnetic energy estimated from EIT dimming volume during eruption was 2.0×10^{31} ergs;
- AR8210 constituted classic delta-spot configuration; main spot in AR8210 had large negative polarity, and it appeared to rotate relative to surrounding magnetic structures;
- Sequence of cancellation events took place between central spot and newly emerging magnetic features of opposite polarity in surrounding region;
- Flux emergence and subsequent cancellation may have been responsible for triggering solar eruption!

WIND/Waves Data for 1998 May 2 Event

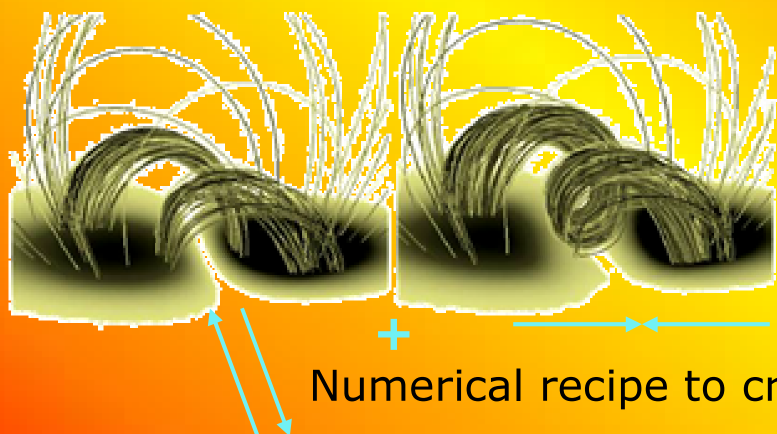


Following the flare, there was relatively intense interval of moving type-IV event (from ejecta itself). Emission is seen from top of the band (14 MHz) down to ~ 8 MHz and at ~ 14:05-15:50 UT. At lower frequencies, there are two different episodes of type II-like emissions: first is in the 4-3 MHz range at ~ 14:15-14:45 UT; and second episode is a bewildering complex of many narrow-band emissions drifting downward from ~ 3-1 MHz at ~ 16:50-18:30 UT.

At f=4 MHz, n_e=1.98x10^5 cm^{-3}: Saito (1970) model gives R~3.5R_S;
At 14:15 UT, LASCO gives R~4.0R_S. SEP event starts ~14:15 UT!

How to Achieve Solar Eruption?

- 3D simulations of erupting flux ropes (from Amari *et al.* 1999, 2000)



Result: flux rope erupts!

(a) t=450

(b) t=490

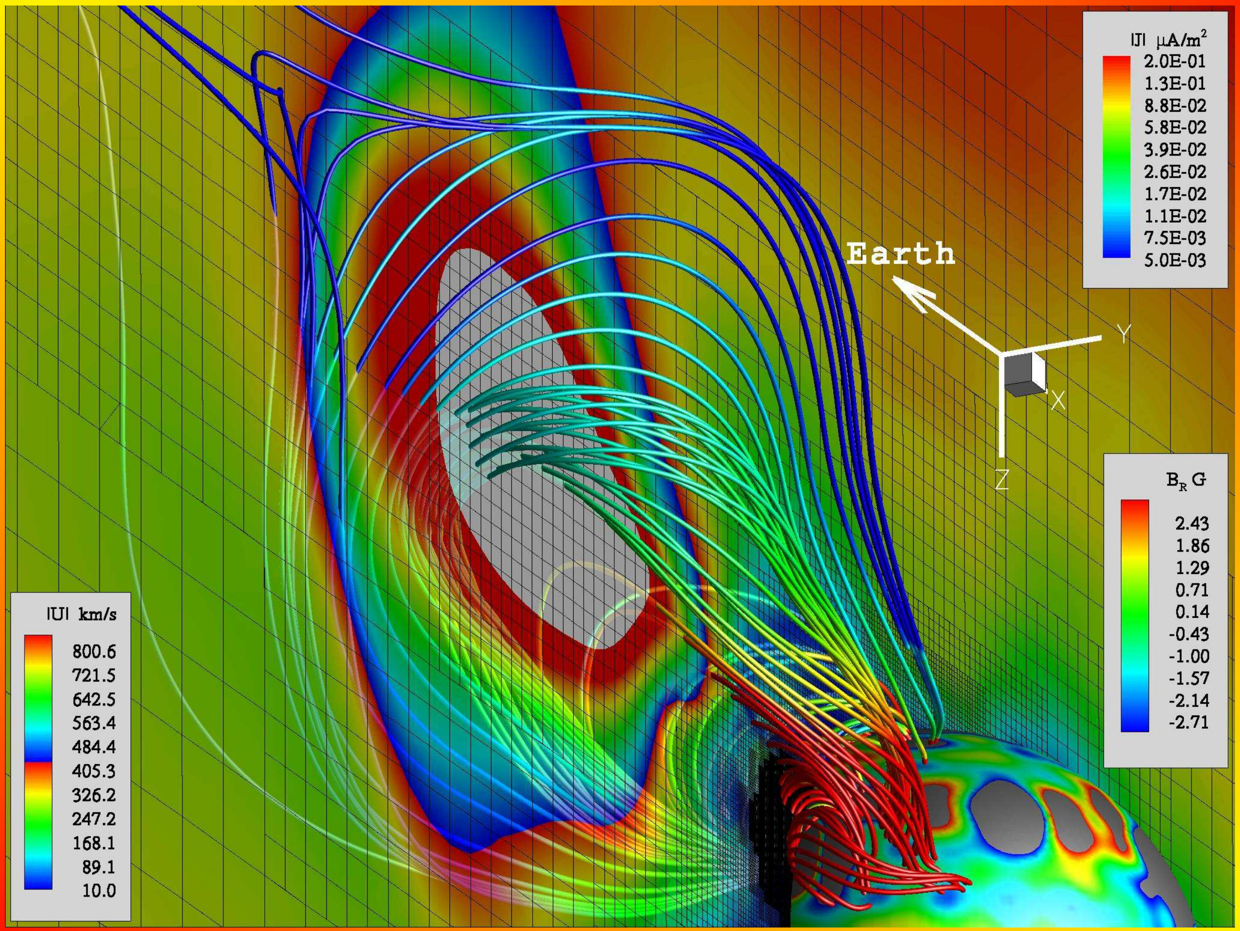
Numerical recipe to create flux rope:

1. Apply shear motions along polarity inversion line:
   - Evolve potential field to non-potential, force-free field;
   - Build energy in sheared field needed for solar eruption.
2. Apply converging motions towards polarity inversion line:
   - Field lines begin to reconnect and form flux rope;
   - Some energy (~8-17%) built during shearing phase is converted into heat and kinetic energy of plasma bulk motions.

Numerical Setup & Performance

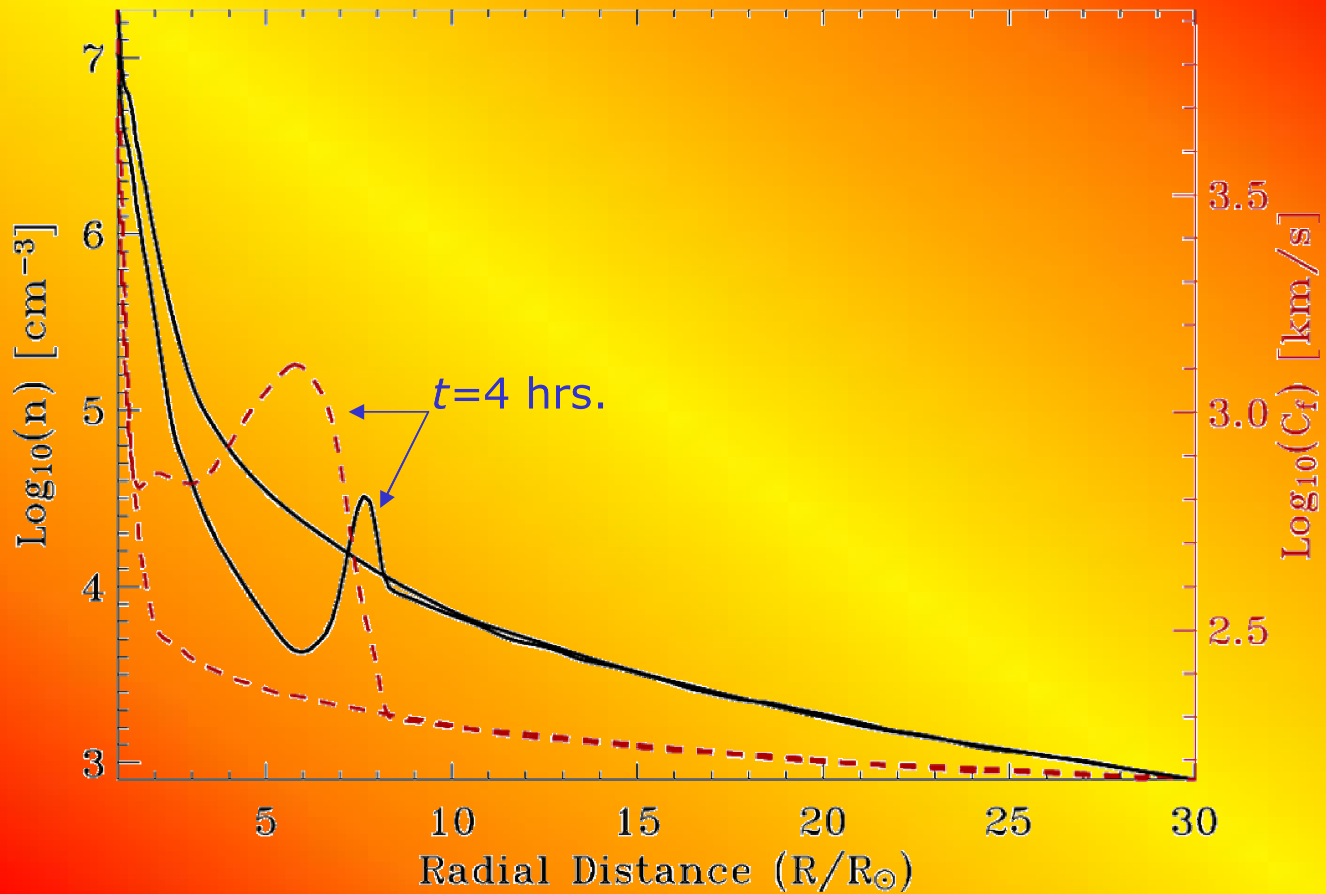
- Computations performed in cubic box: $\{-30<x<10, -20<y<20, -20<z<20\}R_S$.
- Non-uniform Cartesian block-adaptive grid:
  - 9 levels of body-focused refinement with finest cells near Sun;
  - 2 additional levels of refinement in vicinity of AR8210 to better resolve boundary motions;
  - Total number of cells of 3,116,352;
    - smallest cell-size of $4.883\times10^{-3}R_S$;
    - largest cells-size of $2.5R_S$;
  - Numerical resolution increased along direction of flux rope propagation by adding 25% more cells (total of 3,890,944) via 4 levels of refinement (finest cells of size $0.156R_S$=109,200km).
- Boundary conditions describe:
  - "Impenetrable" and highly conducting spherical inner body at $R=R_S$;
  - All velocity components at surface fixed at zero as MHD solution evolves towards steady-state (solar rotation not applied);
  - Small positive mass flow through inner boundary is allowed to balance mass loss by solar wind;
  - Line-tied boundary condition used for magnetic field; field remains frozen to plasma, except in regions where flux cancellation occurs;
  - Zero-gradient condition applied to all variables at outer boundaries.
- Performance:
  - CPU power: 15 dual AMD Athlon 1900XP nodes, 1,024MB RAM per node;
  - Simulated time: 7.12hrs;
  - Running time: 441hrs CPU time; **- far from doing real time simulations at present!**

View of Eruption at t=3 hrs.



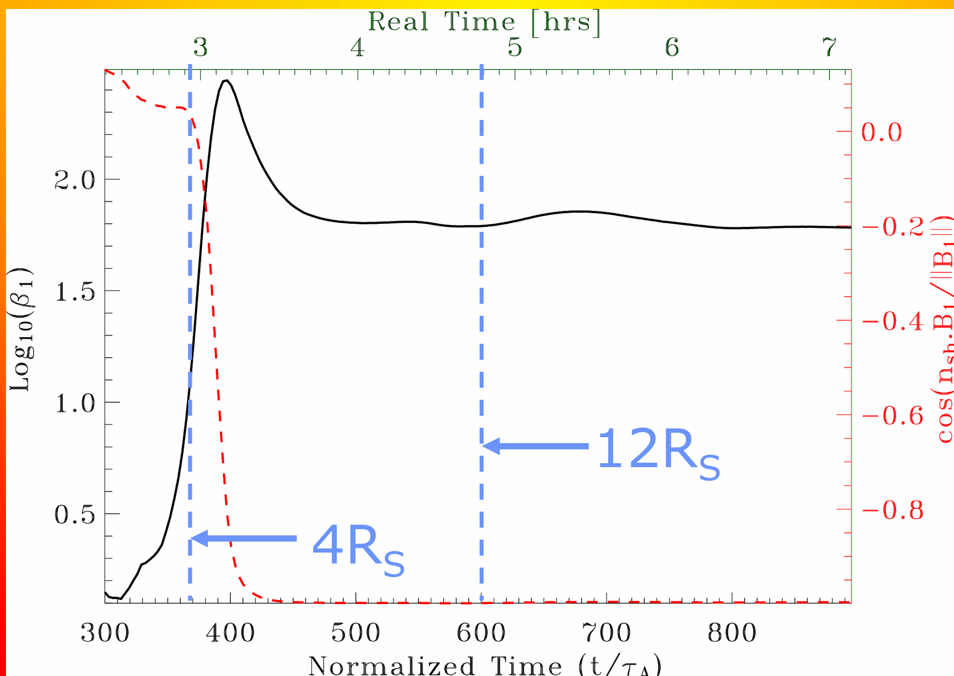
Solid lines are magnetic field lines; false color code shows magnitude of current density. Flow speed is shown on translucent plane given by y=0. Values in excess of 1,000 km/s are blanked and shown in light grey. Inner sphere corresponds to $R=R_S$; color code shows distribution of radial magnetic field. Regions with radial field strength greater than 3 Gauss are blanked.

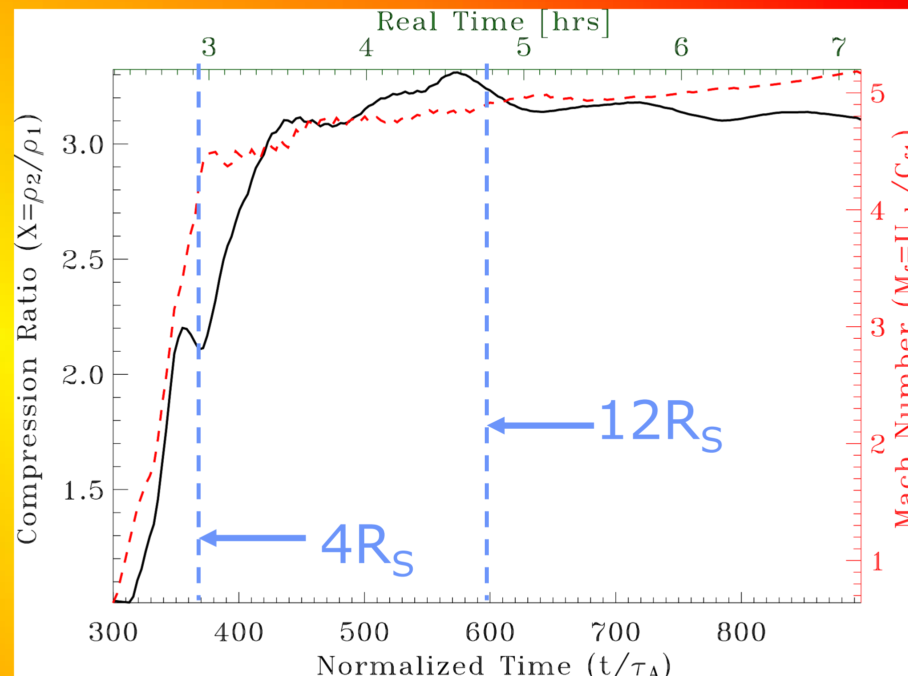
Dynamic Profiles of Plasma Density and Fast-wave Speed



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

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.