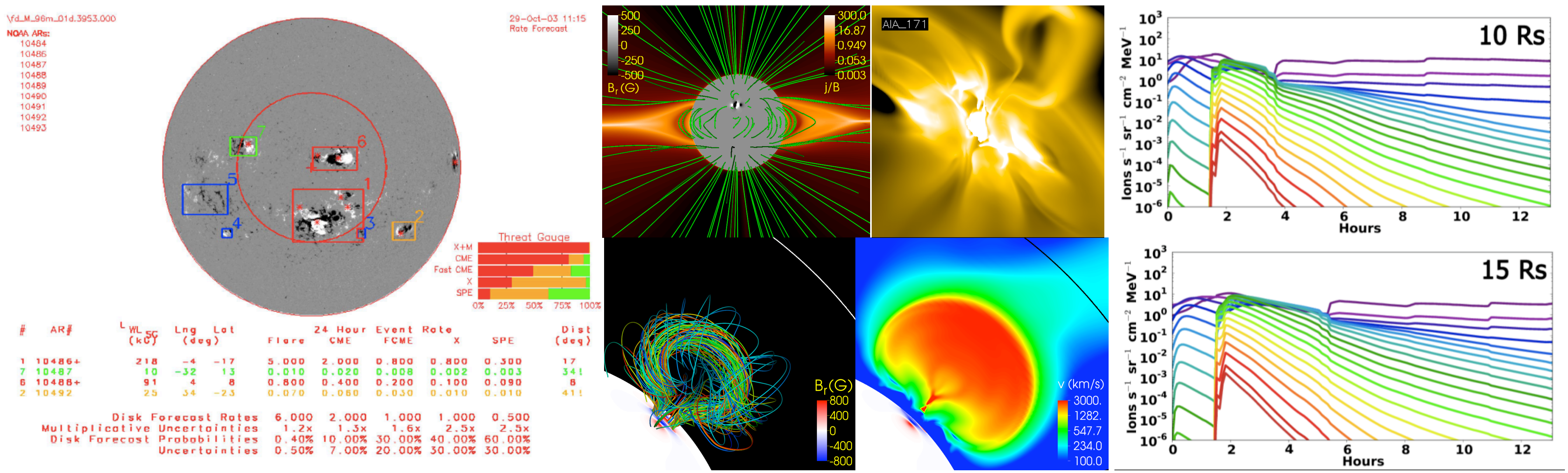
Towards a Predictive Model for Solar Particle Events*



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Introduction

- Solar Particle Events (SPEs) are an important space weather phenomena
  - Can damage satellite instrumentation
  - Hazardous for extravehicular maneuvers by astronauts in Earth orbit
  - Major hazard for eventual manned interplanetary space travel
- They also represent one of the most difficult phenomena to predict:
  - Their generation spans very different plasma regimes and large regions of the heliosphere
  - We lack a detailed physical understanding of important aspects of the generation process
- Nevertheless, we believe that prediction of SPEs is not doomed to be a futile exercise
- We are developing tools that may allow useful predictions of SPEs in the future

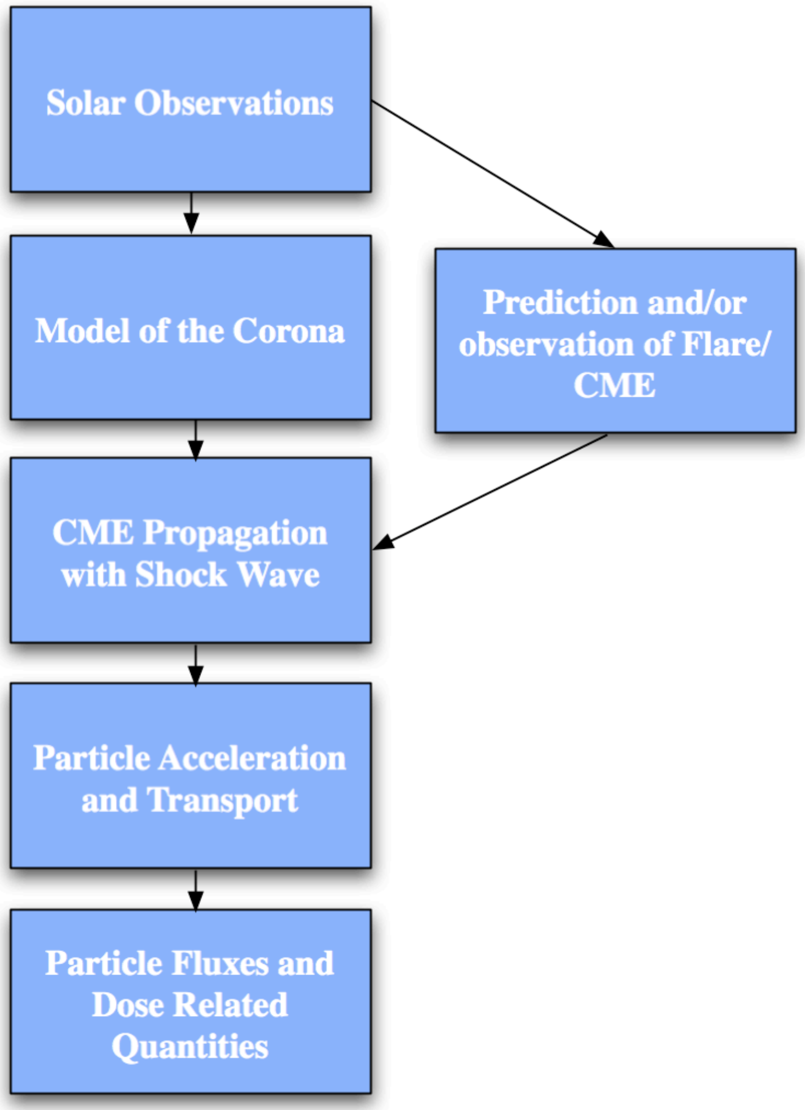
Why is this problem so difficult?

- Solar Energetic Particles are primarily are associated with Coronal Mass Ejections (CMEs)
  - Most scenarios involve shock acceleration
  - Flares also play a role. Reconnection?
  - Simple understanding of gradual vs impulsive = CME vs. Flare. This seems not to describe all events
- The particles arrive in minutes to hours after the start of the event
- This requires warning of an imminent eruption, not just identification of a CME - but we can't predict this from first principles
- Not all Fast CMEs produce SPEs
  - Either sufficient particles not generated or lack of connectivity
  - Need to model initial CME rise, propagation,
  - Need model to particle generation and transport

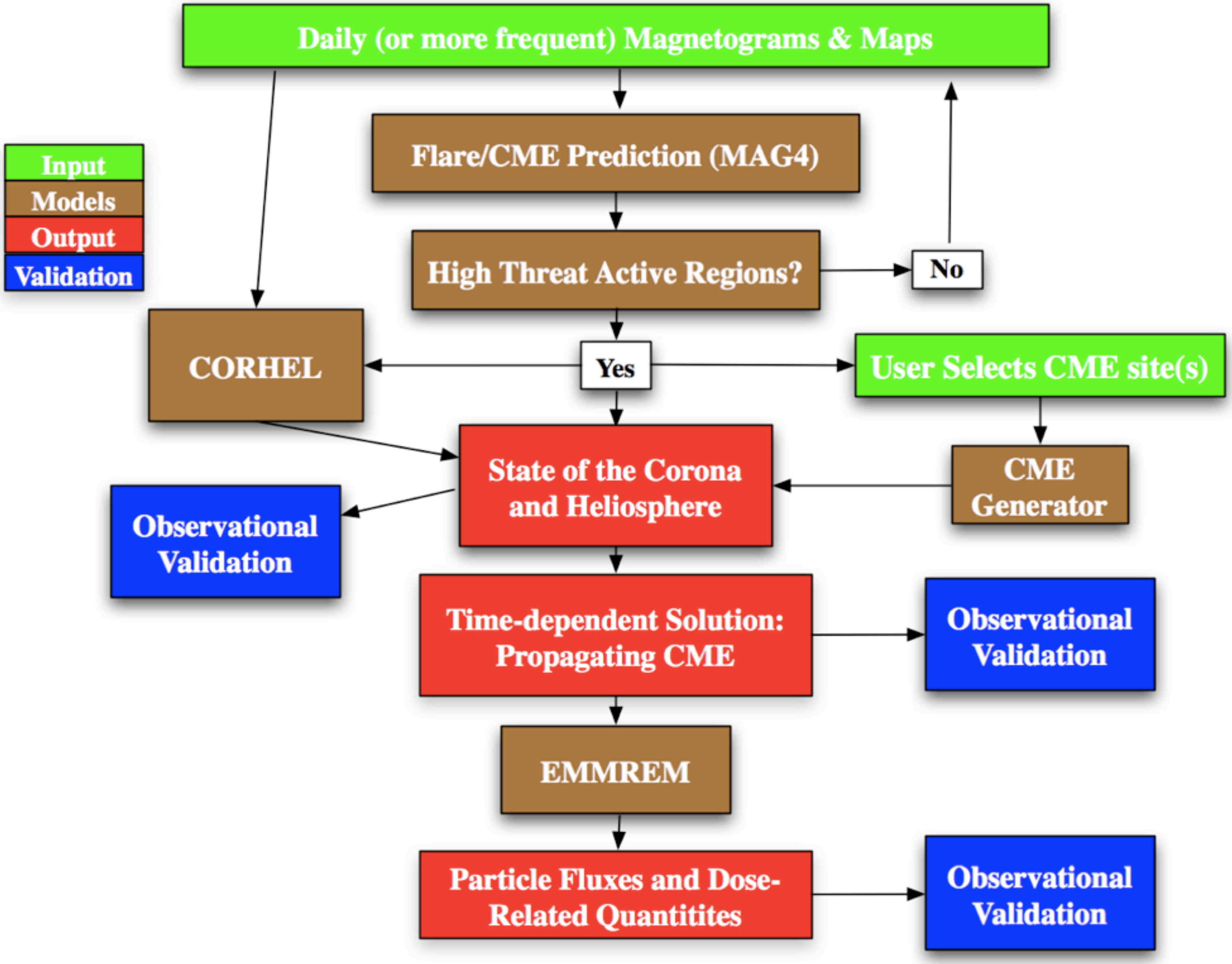
Required Elements:

- A forecast of a CME prior to eruption
- Description of the CME, including shock formation and propagation
- This in turn requires a detailed description of the background corona and solar wind
  - Accurate modeling of Alfven speed
  - Connectivity to Earth and elsewhere
- An SEP generation and transport model coupled to the shock
- Dose rates for different materials for the simulated particles

We need to be able to routinely simulate solar particle events



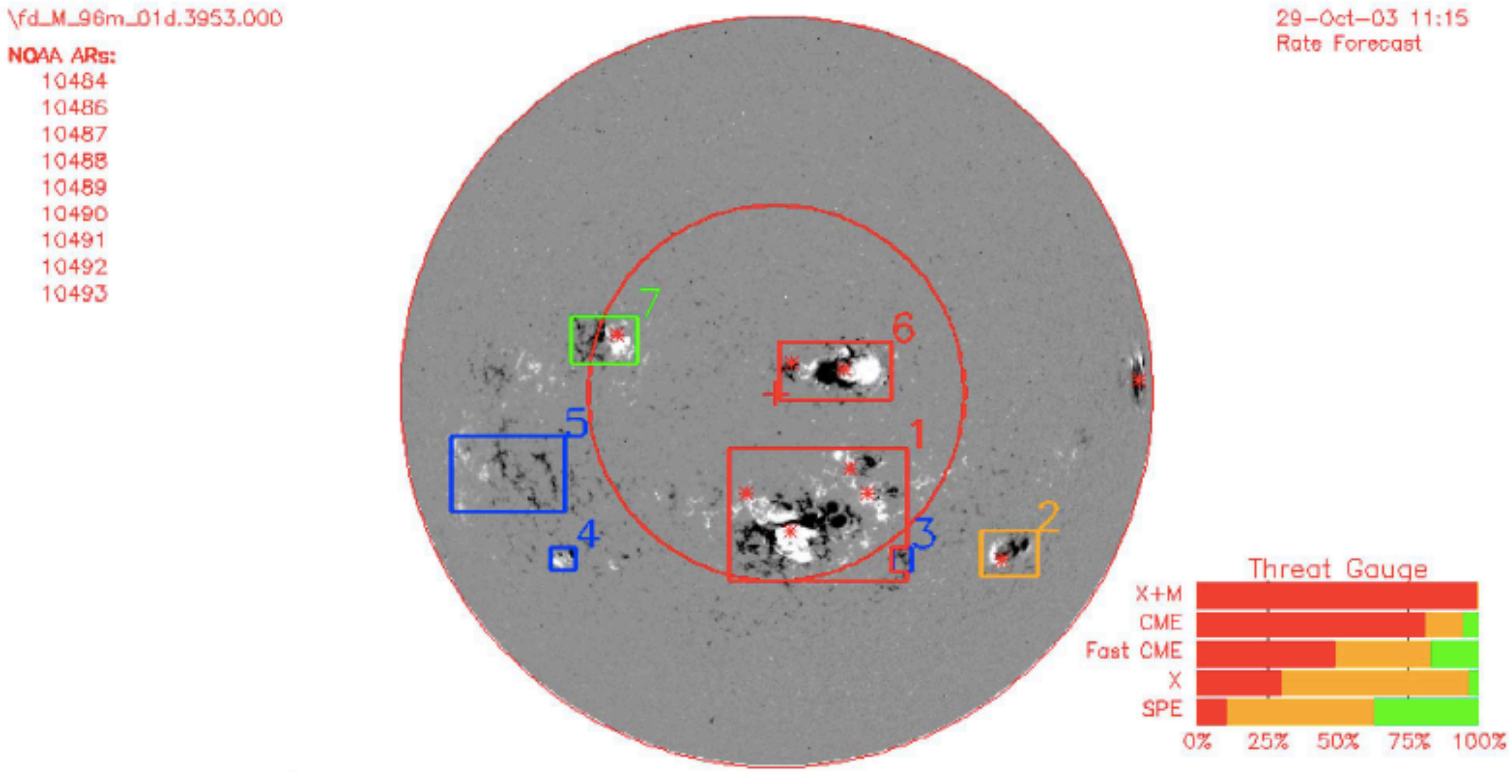
A Proposed Prediction Scheme for SPEs



MAG4: A Tool For Forecasting Major Flares, CMEs and SPEs

- Empirical tool utilizes relationship between event rate and a proxy for Active Region's free magnetic energy (W_f).
  - Actually derived from line-of-sight magnetograms (MDI, HMI).
  - Highly nonpotential ARs (large W_f) are known to be associated with major flare/CME events.
  - W_f is closely related to sheared magnetic fields.
  - Falconer et al. (2008) found that strong gradients in B_r are closely related to strong gradients in transverse B, and hence W_f.
- Tool described by Falconer et al. (2011); version delivered to NASA Satellite Radiation Analysis Group (SRAG)
- Demonstrated at http://www.uah.edu/cspar/research/mag4-page/
- Further empirical relationships being investigated to improve the tool (Falconer et al. 2012).

MAG4: A Tool For Forecasting Major Flares, CMEs and SPEs



#	AR#	WL (kG)	Lng (deg)	Lat	24 Hour Event Rate Flare	CME	FCME	X	SPE	Dist (deg)
1	10486+	218	-4	-17	5.000	2.000	0.800	0.800	0.300	17
7	10487	10	-32	13	0.010	0.020	0.008	0.002	0.003	34!
6	10488+	91	4	8	0.800	0.400	0.200	0.100	0.090	8
2	10492	25	34	-23	0.070	0.060	0.030	0.010	0.010	41!

	Flare	CME	FCME	X	SPE
Disk Forecast Rates	6.000	2.000	1.000	1.000	0.500
Multiplicative Uncertainties	1.2x	1.3x	1.6x	2.5x	2.5x
Disk Forecast Probabilities	0.40%	10.00%	30.00%	40.00%	60.00%
Uncertainties	0.50%	7.00%	20.00%	30.00%	30.00%

Display for Mag4

CORHEL: CORona-HELiosphere

- A suite of coupled models and tools for describing the solar corona and solar wind
  - Allows input from 7 different Solar magnetographs
  - Processes synoptic maps into boundary data for calculations
  - Three coronal model choices (WSA/Potential field, MAS polytropic, MAS thermodynamic
  - Two heliospheric model choices (Enlil, MAS)
  - Can provide cone model CMEs
  - Outputs observable quantities for validation
  - Available at CCMC and http://www.predsci.com/hmi http://www.predsci.com/stereo

EMMREM: Earth-Moon-Mars Radiation Module

- Characterizes time-dependent radiation exposure in the Earth-Moon-Mars and interplanetary space environments (Schwadron et al. 2010). Components:
  - Energetic Particle Radiation Environment Module (EPREM)
  - Baryon Transport Module (BRYNTRN)
  - Input: Solar energetic particle observations
  - Propagates observed time series through the inner heliosphere
  - Derives the flux and dose time series at observers
- Available at CCMC and http://prediccs.sr.unh.edu/
- EPREM - 3D kinetic model for the transport of energetic particles
  - Produce fluxes for diffusive shock acceleration mechanism, energetic particle transport.
  - Modified to take shock or large B gradient from MHD result

Key Challenges

- We need to be able model CMEs more routinely
  - A user should be able to select a region of origin for a CME
  - Initate the CME(s) with a few parameters
- The CME simulations must be performed in a sophisticated coronal model
  - Thermodynamic MHD required:
  - Accurate V_A requires accurate density
  - γ = 5/3 (ratio of specific heats) required for correct jump conditions at shocks
- The CME simulations must be coupled with an SEP generation and tranport model
  - Coupling of CORHEL with EPREM module of EMMREM

CME Models and Simulations

- The mechanism(s) that initiate CMEs are under intense debate.
- It is challenging to perform CME simulations for a real event with "first principles" mechanisms (e.g. breakout, flux cancellation, etc).
- It is difficult to initiate very fast CMEs
- All mechanisms seem to result in an erupting flux rope after initiation
- We are experimenting with inserting flux ropes into coronal configurations, then destabilizing them
- We require simulations in a realistic corona, and destabilization from equilibria
- We would like to disturb the original magnetic flux distribution as little as possible
- Our goal is to develop robust simulations with a limited set of parameters for initiation

MHD Equations
(Improved Energy Equation Model)

$$\nabla \times \mathbf{B} = \frac{4\pi}{c}\mathbf{J}$$

$$\nabla \times \mathbf{E} = -\frac{1}{c}\frac{\partial \mathbf{B}}{\partial t}$$

$$\mathbf{E} + \frac{1}{c}\mathbf{v} \times \mathbf{B} = \eta \mathbf{J}$$

$$\frac{\partial \rho}{\partial t} + \nabla \cdot (\rho \mathbf{v}) = 0$$

$$\rho\left(\frac{\partial \mathbf{v}}{\partial t} + \mathbf{v} \cdot \nabla \mathbf{v}\right) = \frac{1}{c}\mathbf{J} \times \mathbf{B} - \nabla p - \boxed{\nabla p_w} + \rho \mathbf{g} + \nabla \cdot (\nu \rho \nabla \mathbf{v})$$

$$\frac{\partial p}{\partial t} + \nabla \cdot (p\mathbf{v}) = (\gamma - 1)\left(-p \nabla \cdot \mathbf{v} \boxed{- \nabla \cdot \mathbf{q} - n_e n_p Q(T) + H}\right)$$

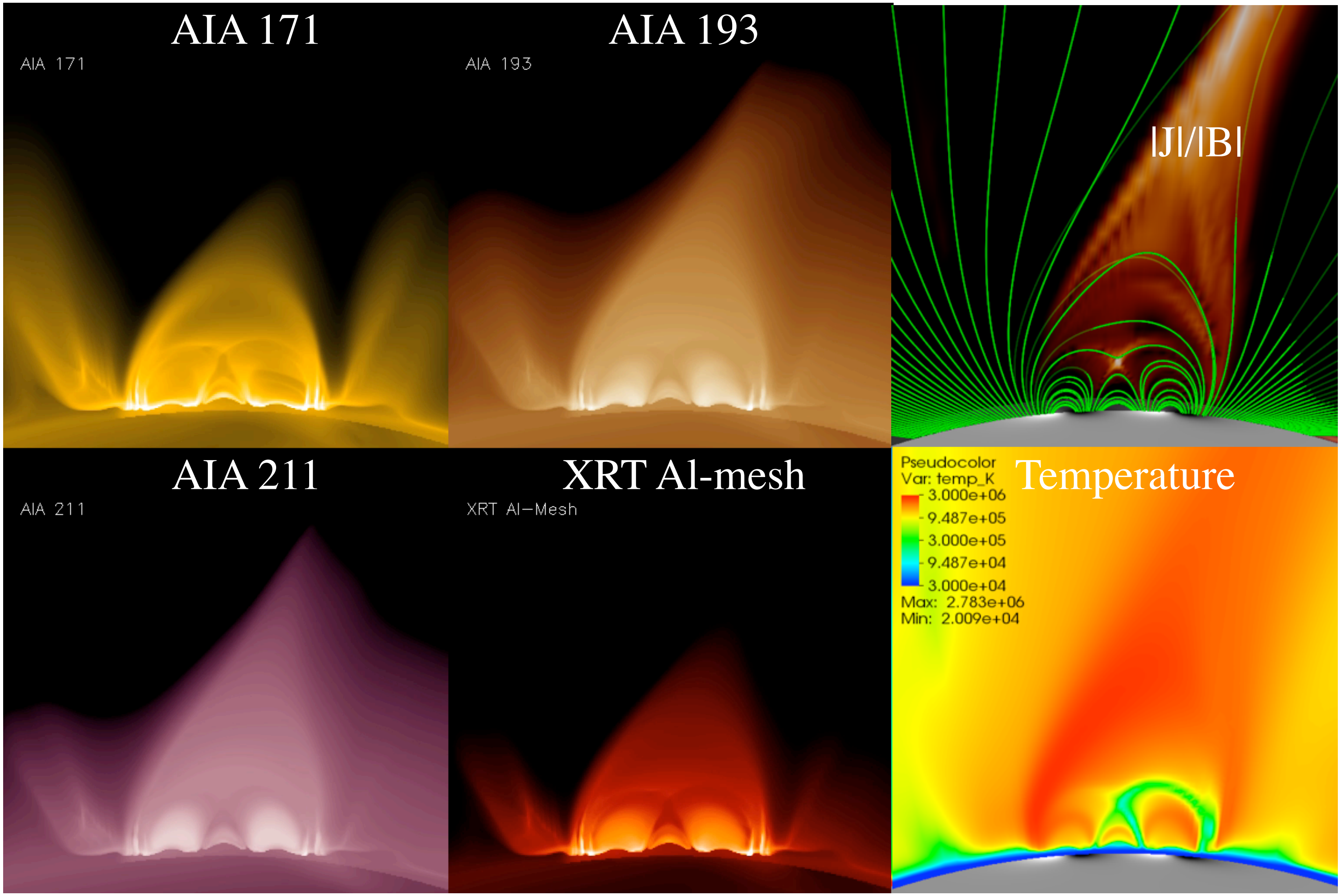
$$\gamma = 5/3$$

$$\mathbf{q} = -\kappa_{\parallel}\hat{\mathbf{b}}\hat{\mathbf{b}} \cdot \nabla T$$ (Close to the Sun, $r \lesssim 10R_S$)

$$\mathbf{q} = 2\alpha n_e T\,\hat{\mathbf{b}}\hat{\mathbf{b}} \cdot \mathbf{v}/(\gamma - 1)$$ (Far from the Sun, $r \gtrsim 10R_S$)

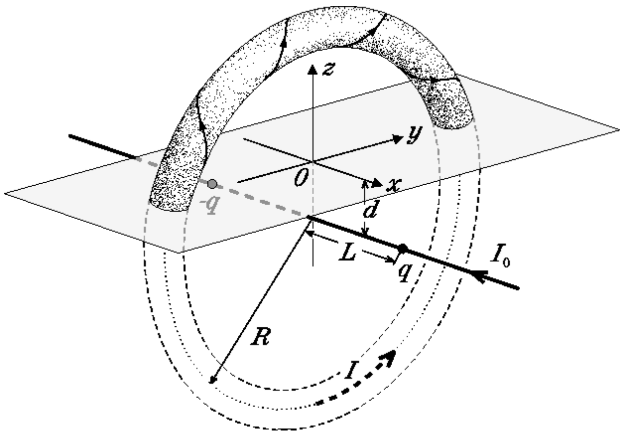
\+ WKB equations for Alfvén wave pressure p_w evolution

Simulated Emission for the Background Corona

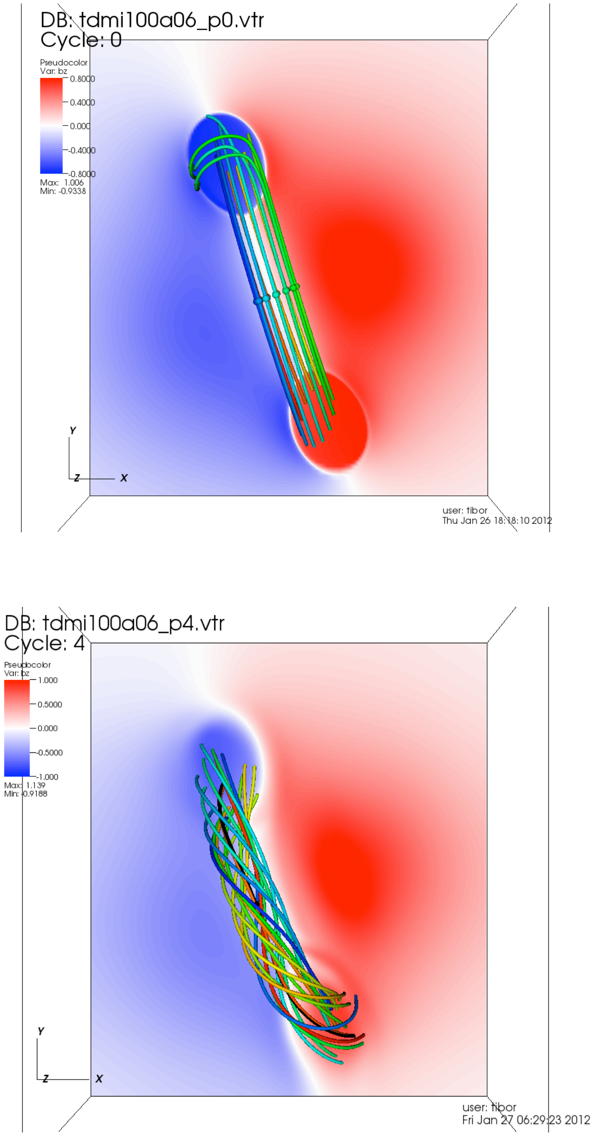


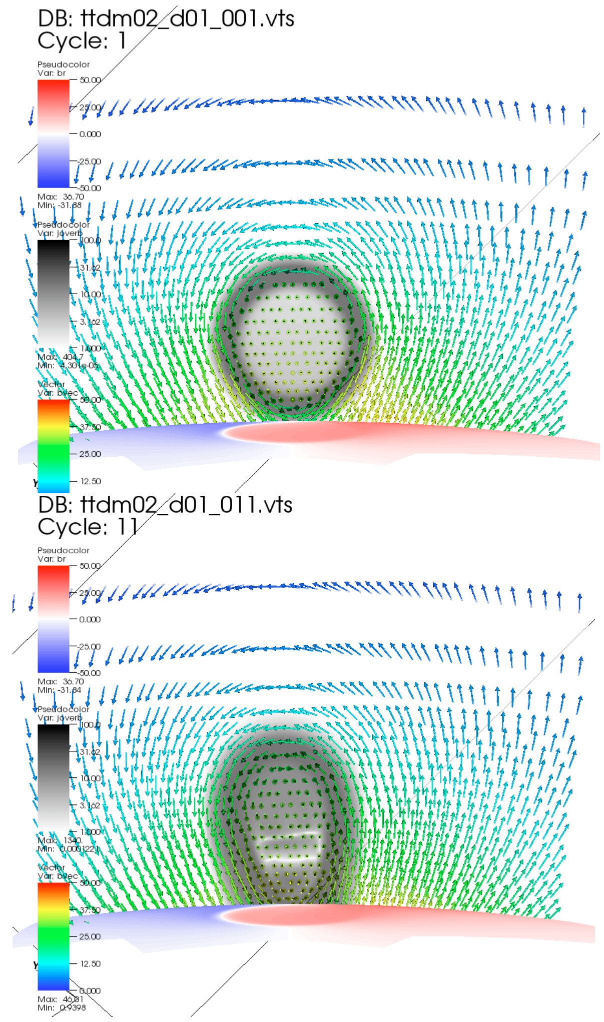
Modeling CMEs with Flux Rope Insertion

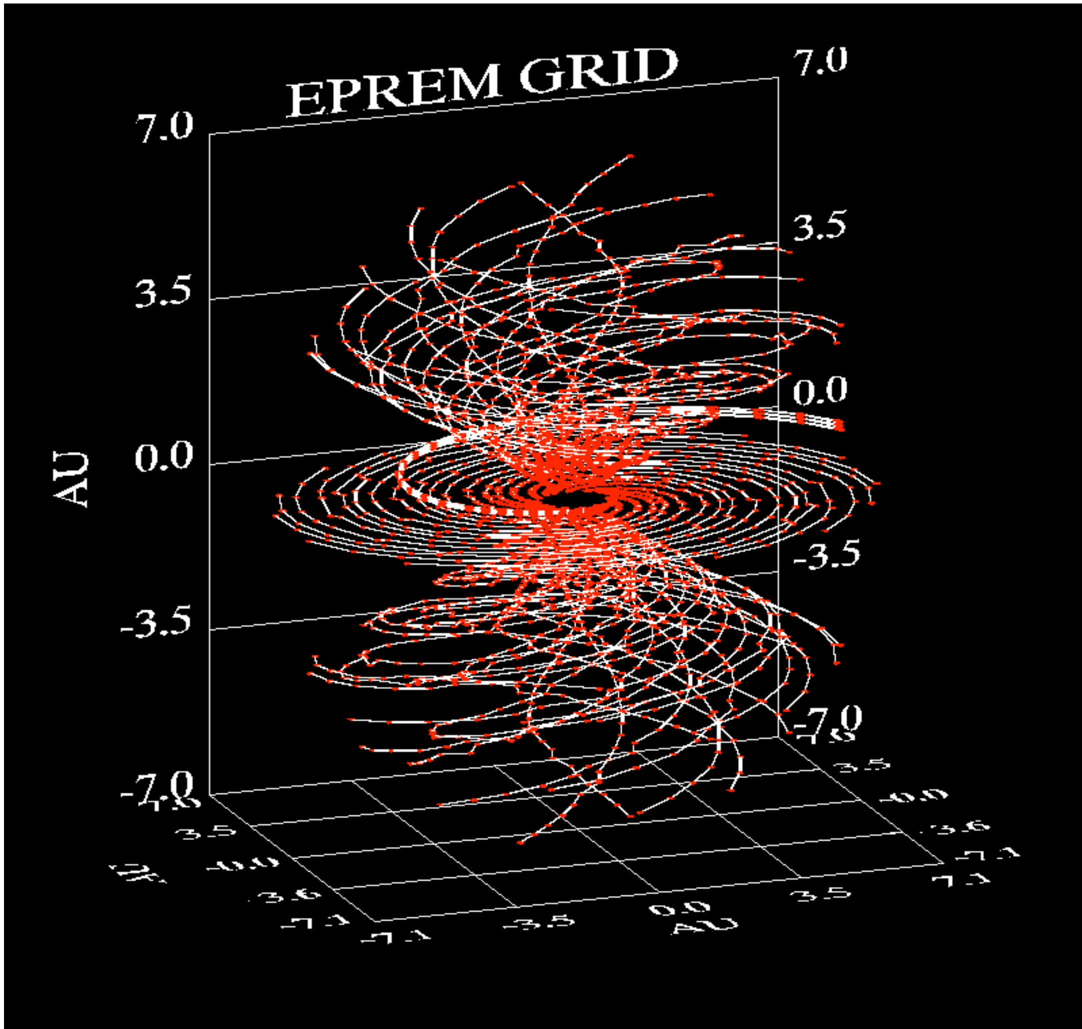
Insert (modified) TD model (in equilibrium) into stabilizing ambient coronal field

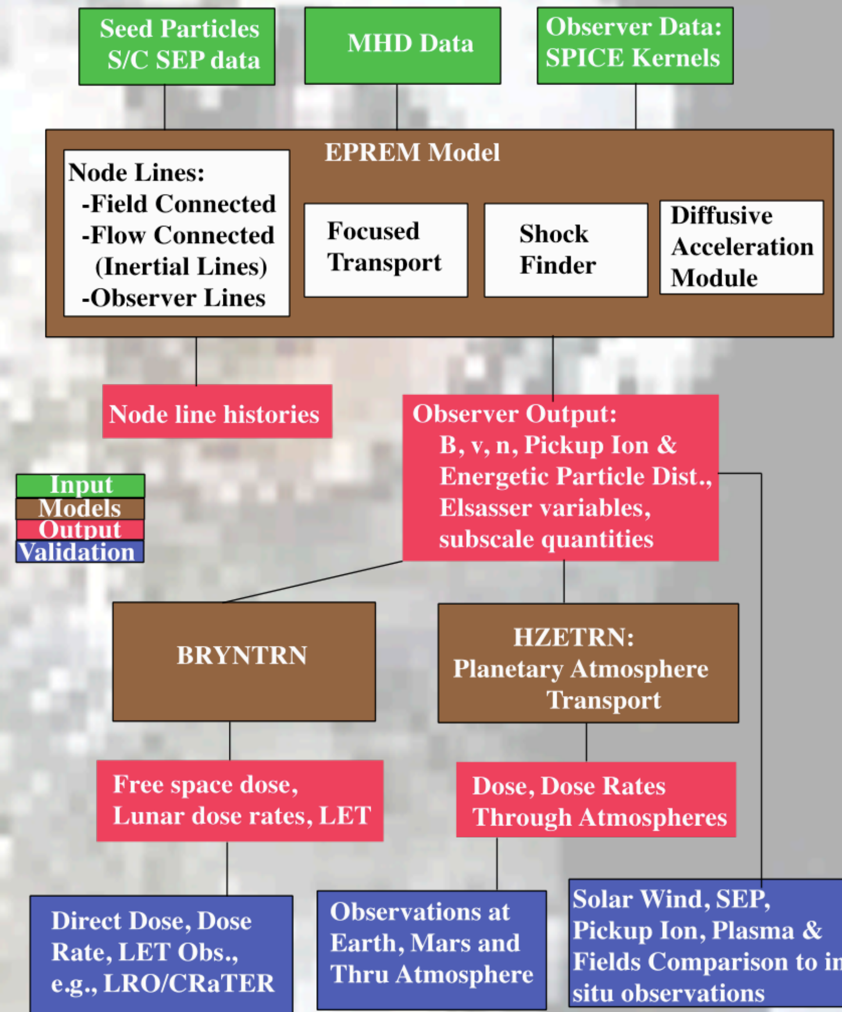


Titov & Démoulin (1999)







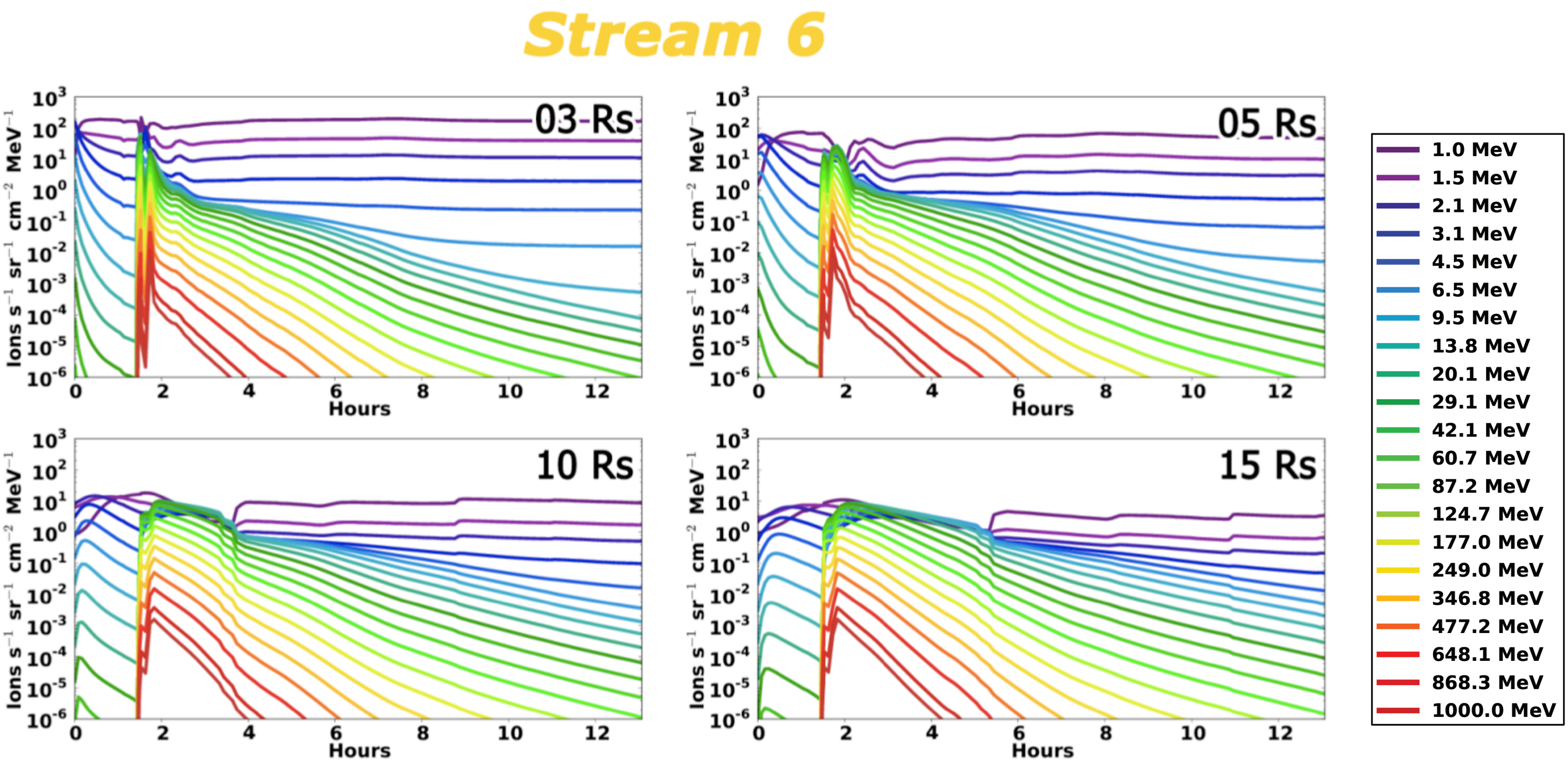


Focused Transport in Lagrangian Frame (Kota, 2005)

$$\left(1-\frac{(\vec{u}\times e_b)v\mu}{c^2}\right)\frac{df}{dt}+v\mu\frac{\partial f}{\partial z}+\frac{(1-\mu^2)}{2}\left[v\frac{\partial \ln B}{\partial z}-\frac{2}{v}e_b\times\frac{d\vec{u}}{dt}+\mu\frac{d\ln(n^2/B^3)}{dt}\right]\frac{\partial f}{\partial \mu}+$$

$$\left[-\frac{\mu e_b}{v}\times\frac{d\vec{u}}{dt}+\mu^2\frac{d\ln(n/B)}{dt}+\frac{(1-\mu^2)}{2}\frac{d\ln B}{dt}\right]\frac{\partial f}{\partial \ln p}=\frac{\partial}{\partial \mu}\left(\frac{D_{\mu\mu}}{2}\frac{\partial f}{\partial \mu}\right)+S$$

SEP Acceleration and Propagation



Summary

- This poster presents a plan for routinely simulating solar particle events
- It combines both empirical and physics-based approaches
- It relies on the coupling of recently developed tools (MAG4, CORHEL, EMMREM) as well as new CME simulations in CORHEL
- We have successfully coupled CORHEL and EMMREM and performed simulated particle events
- We have tons of work left to do, especially validation
- I think an approach like this is necessary if we are going to make serious progress on this problem
- Each element of the scheme can be improved or eventually replaced as our science improves

Extra Slides

MAS-EPREM Coupling: A Preliminary Case

- MAS (Magnetohydrodynamic Algorithm outside a Sphere) is the coronal MHD model in CORHEL
  - We used a simulation of the May 12, 1997 CME to test the coupling
  - The simulation was performed with the thermodynamic MHD model
- We supplied the 3D, time-dependent solution as a sequence of files to EPREM (Energetic Particle Radiation Environment Module of EMMREM)
  - Data interpolated onto EPREM Lagrangian grid
  - Shock identification performed in EPREM
  - EPREM converted to run on GPUs for significant speed-up
- Solution in inner corona (plan to extend to 1 AU)

A Configuration-Preserving TD Model

Time sequence showing eruption of the flux rope

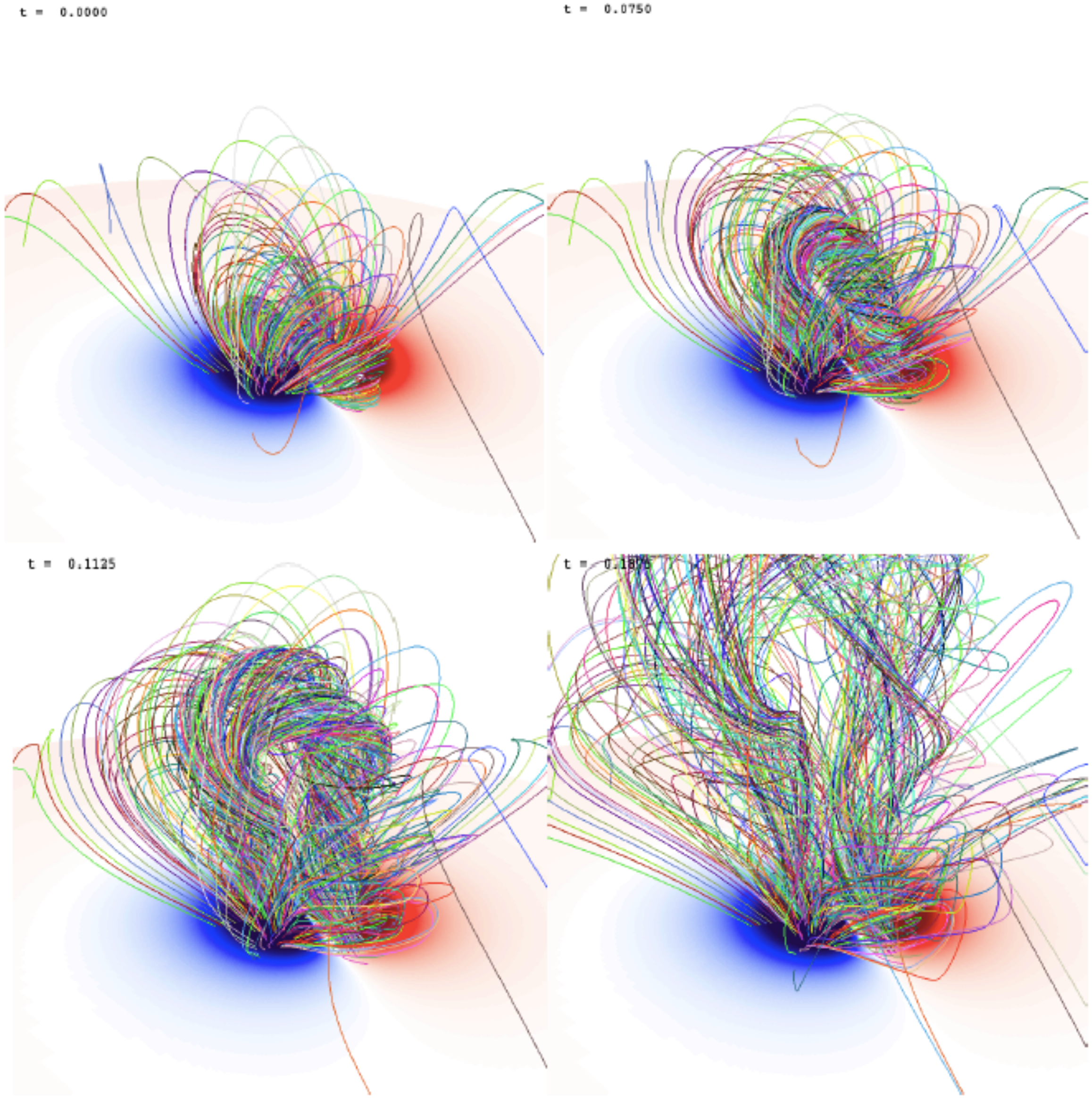
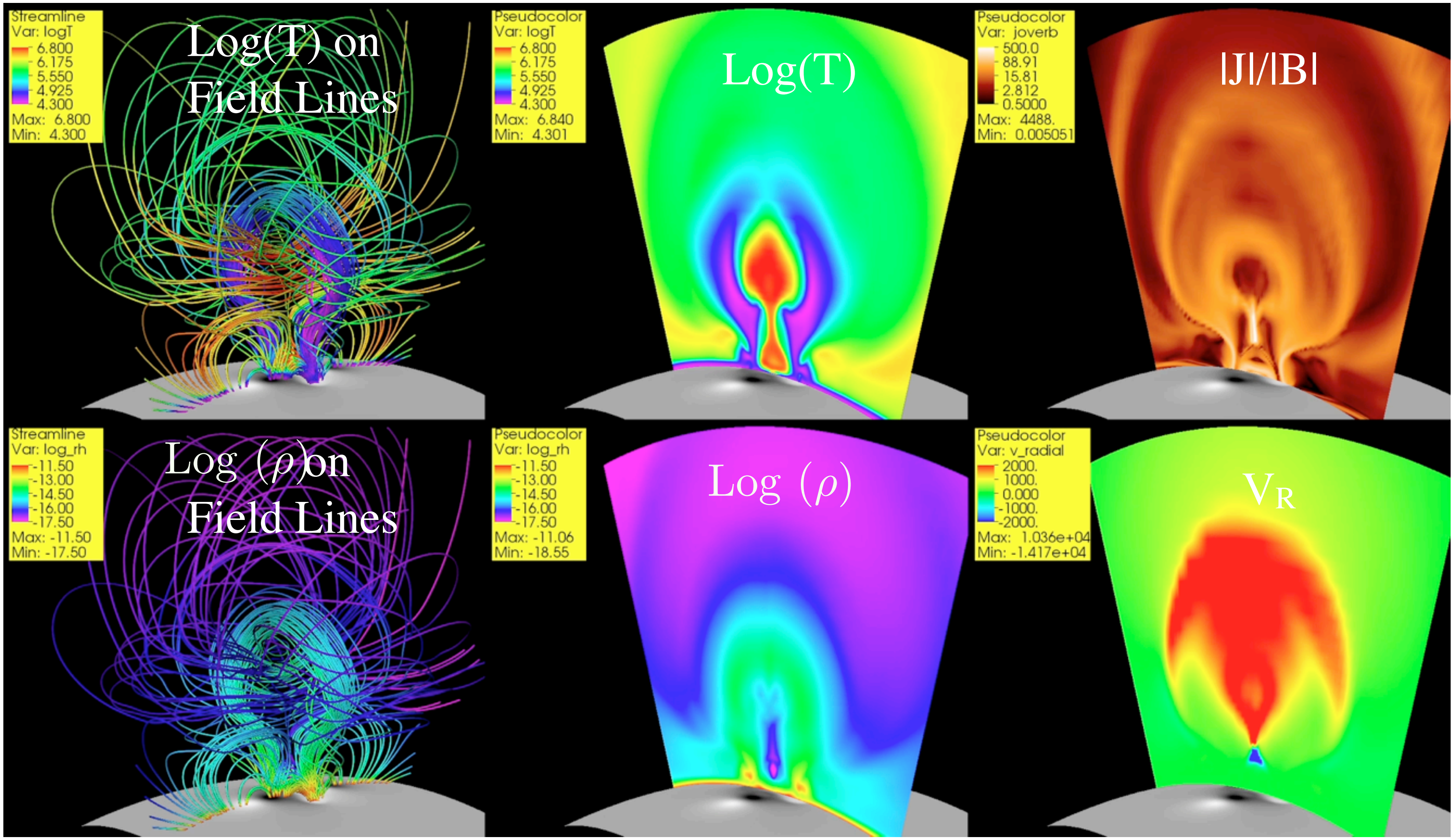


Figure 7. Time sequence showing the rapid eruption of the active region when the TD flux rope that is inserted is beyond the stability threshold.

Eruption of the Configuration:

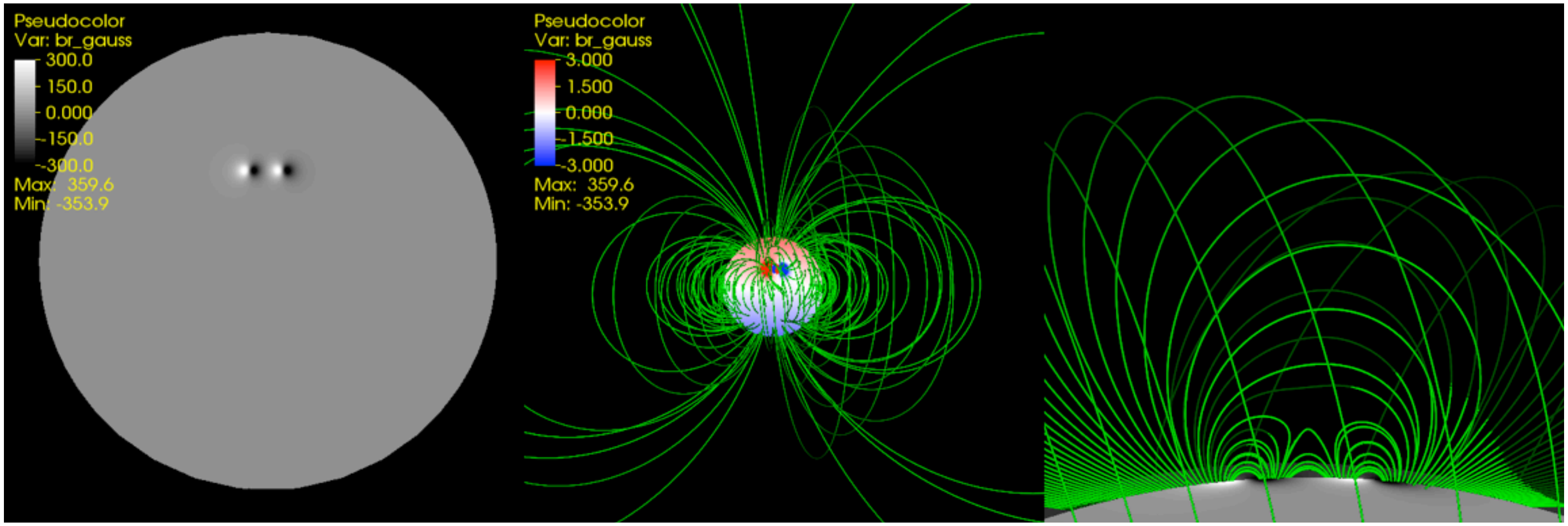


- Converging flows near the polarity inversion line leads to flux cancellation
- Configuration erupts when a threshold is exceeded

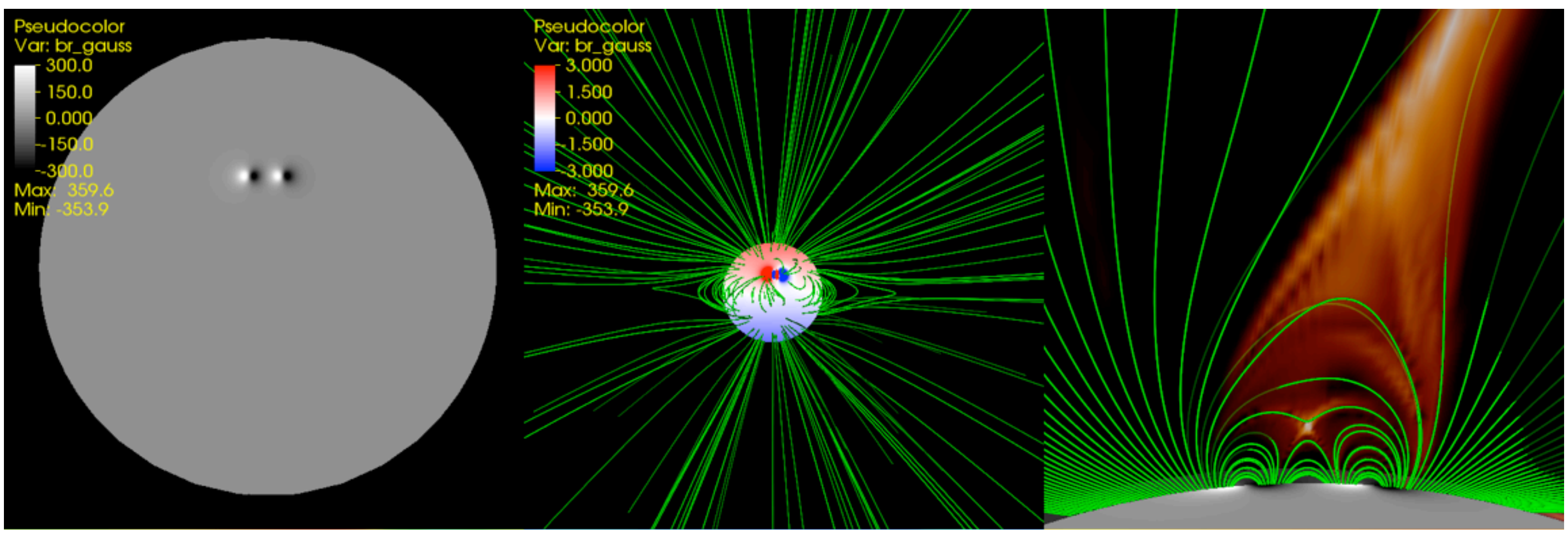
Introduction (continued)

- There is already a useful tool for short-term predictions:
  - Posner et al. (2009): employs measurements of precursor relativistic electrons
  - Up to 1 hour warning
- Here we are interested in longer-term (several hours to days)
- We are interested in physics-based models, recognizing that empirical models/techniques must also be incorporated
- What do I mean by useful predictions?
  - Probablistic forecasts of the likelihood of major event(s)
  - Probablistic forecasts of significant all-clear times
  - This may be possible without detailed physical understanding of all processes
- While the difficulty is high, the bar is set somewhat low now - anything to improve present capabilities will be useful

Modeling a fast CME: Initial field & MHD solar wind relaxation

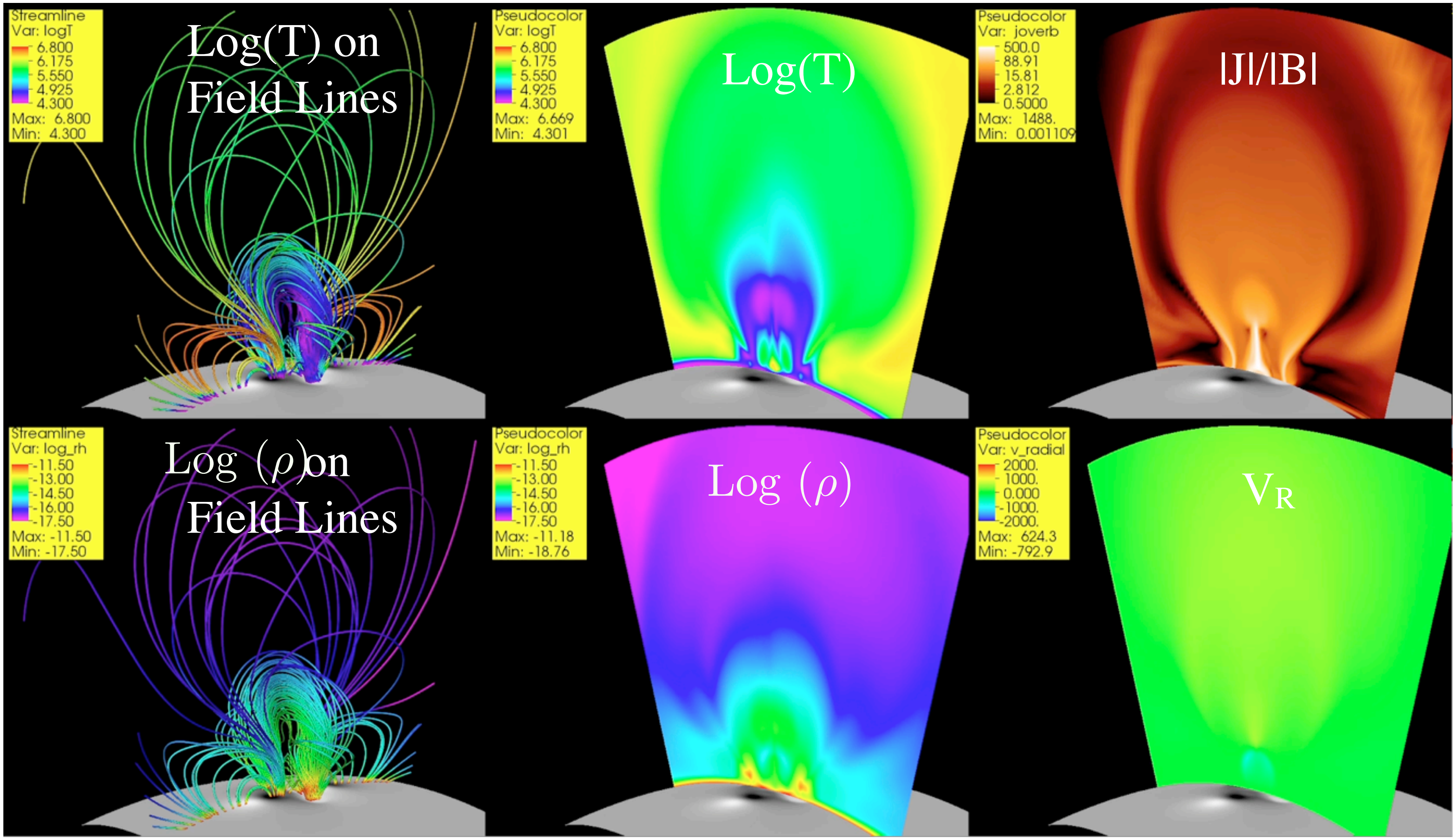


global dipole + quadrupolar active region



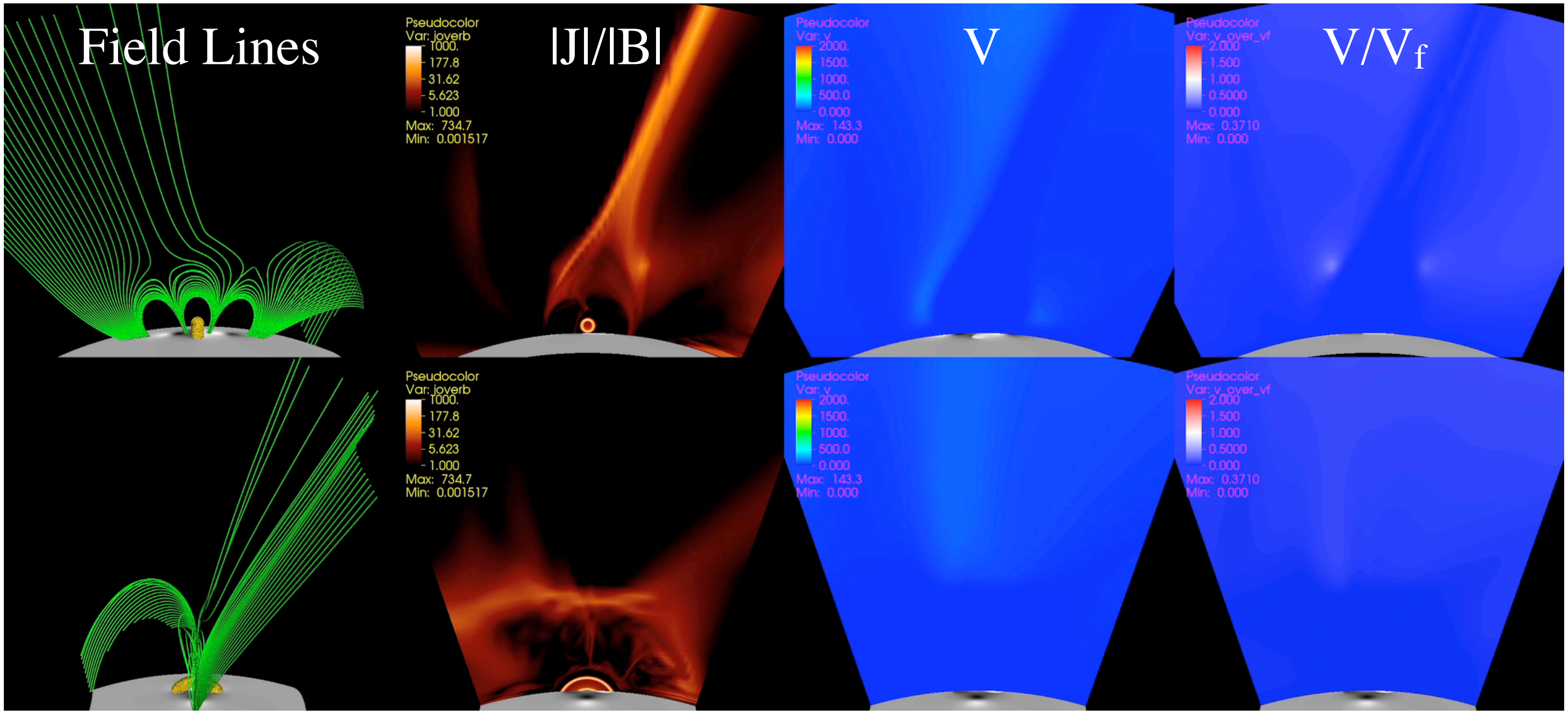
relaxation: coronal field opens up + streamer forms above active region

Eruption of the Configuration: Pre-Flare State

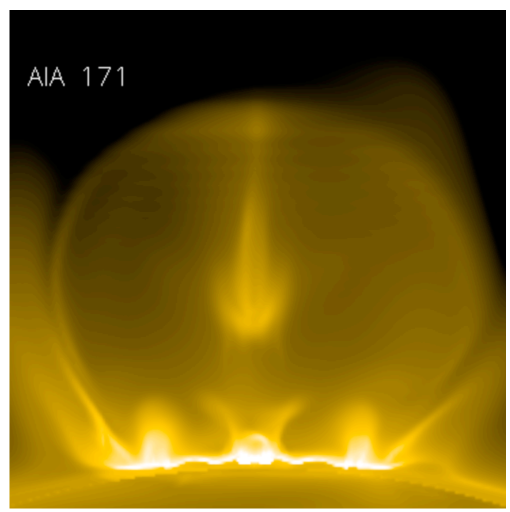


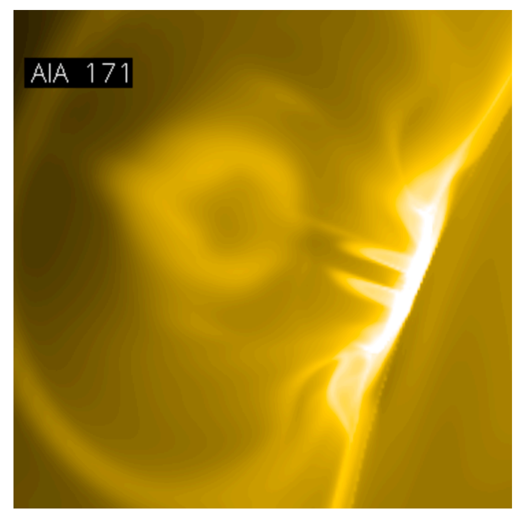
- Converging flows near the polarity inversion line leads to flux cancellation
- Configuration erupts when a threshold is exceeded

Fast CME Creates Shock Wave

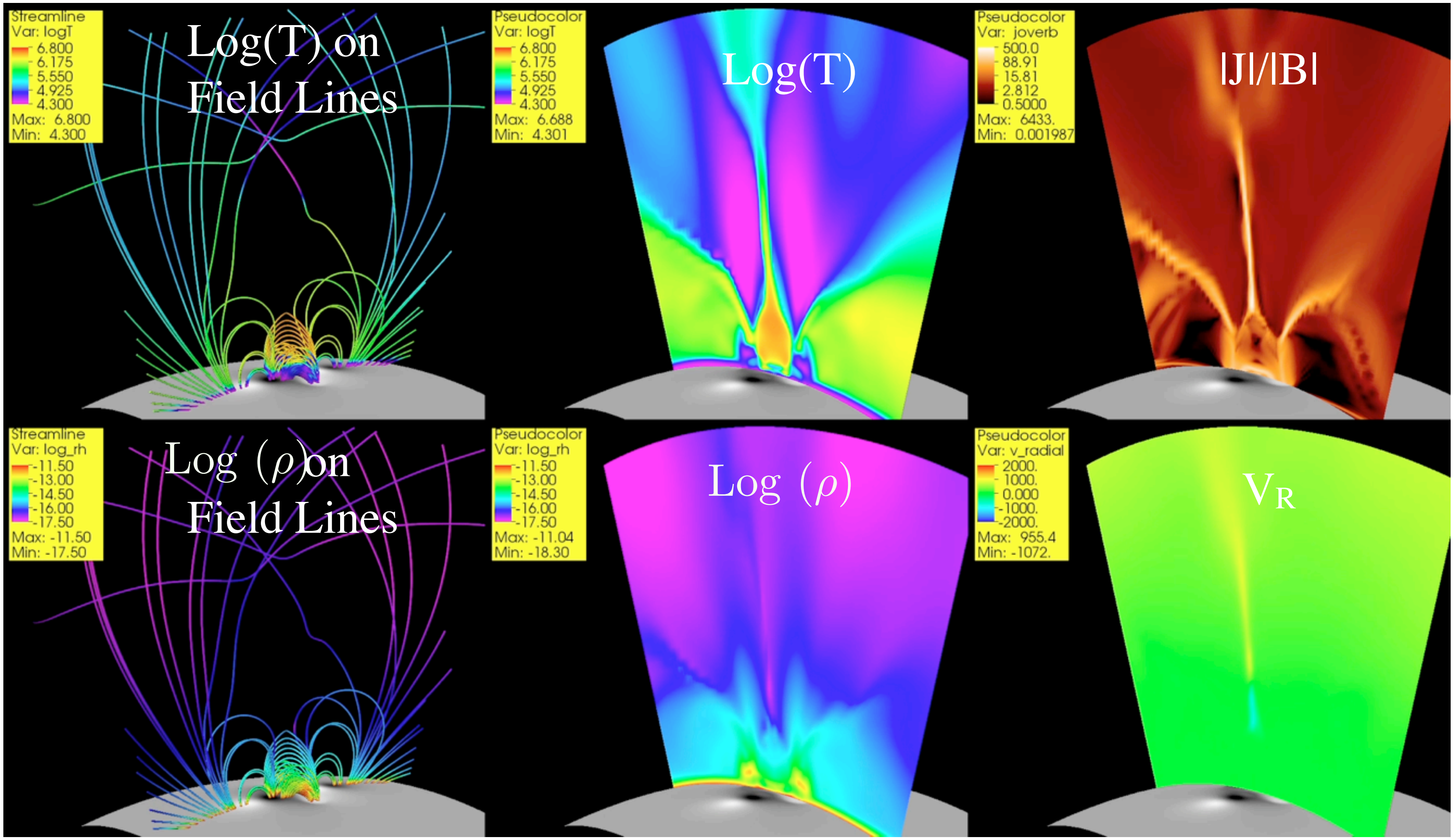


- B_max ≈ 600 G
- AR flux ≈ 2 x10^{22} Mx
- max. CME speed ≈ 2000 km/s
- W release ≈ 1.5 x10^{32} ergs



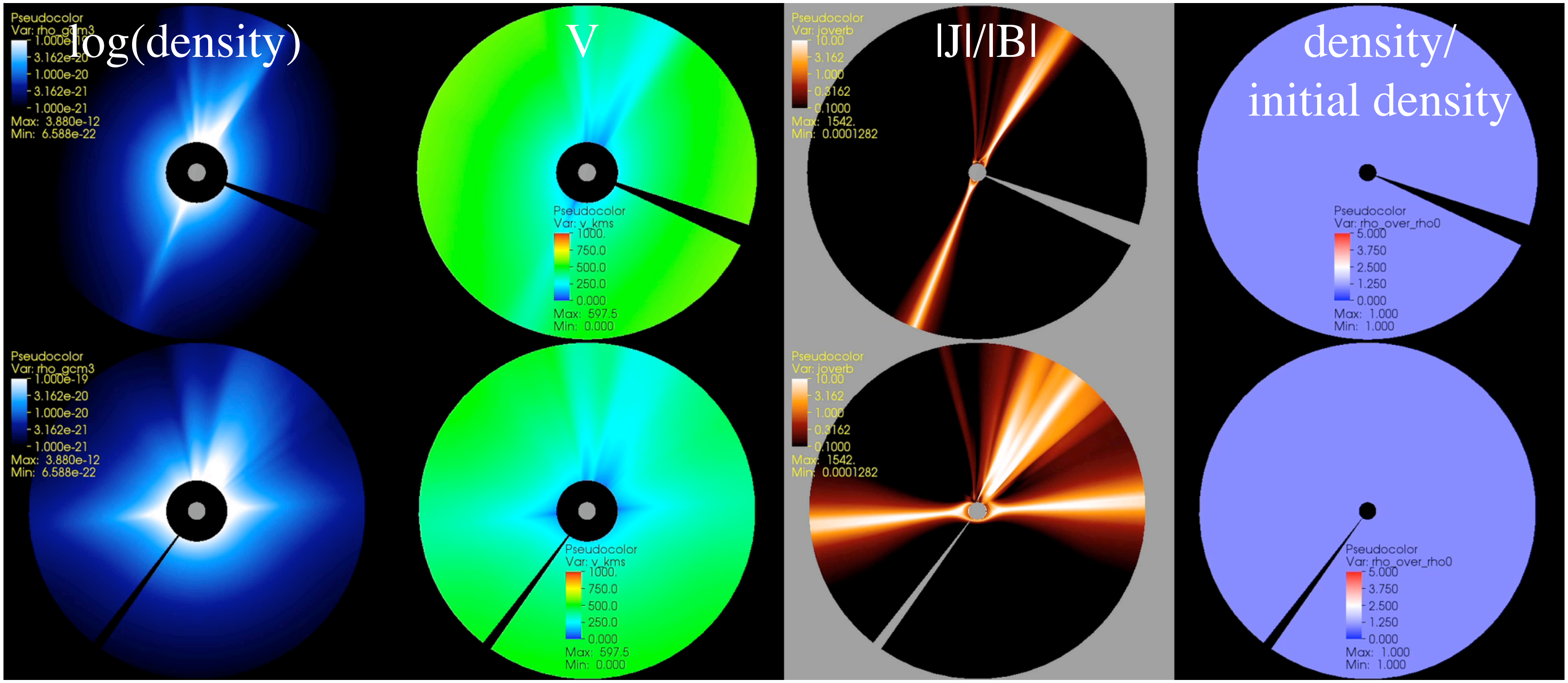


Eruption of the Configuration: Post-Flare State



- Converging flows near the polarity inversion line leads to flux cancellation
- Configuration erupts when a threshold is exceeded

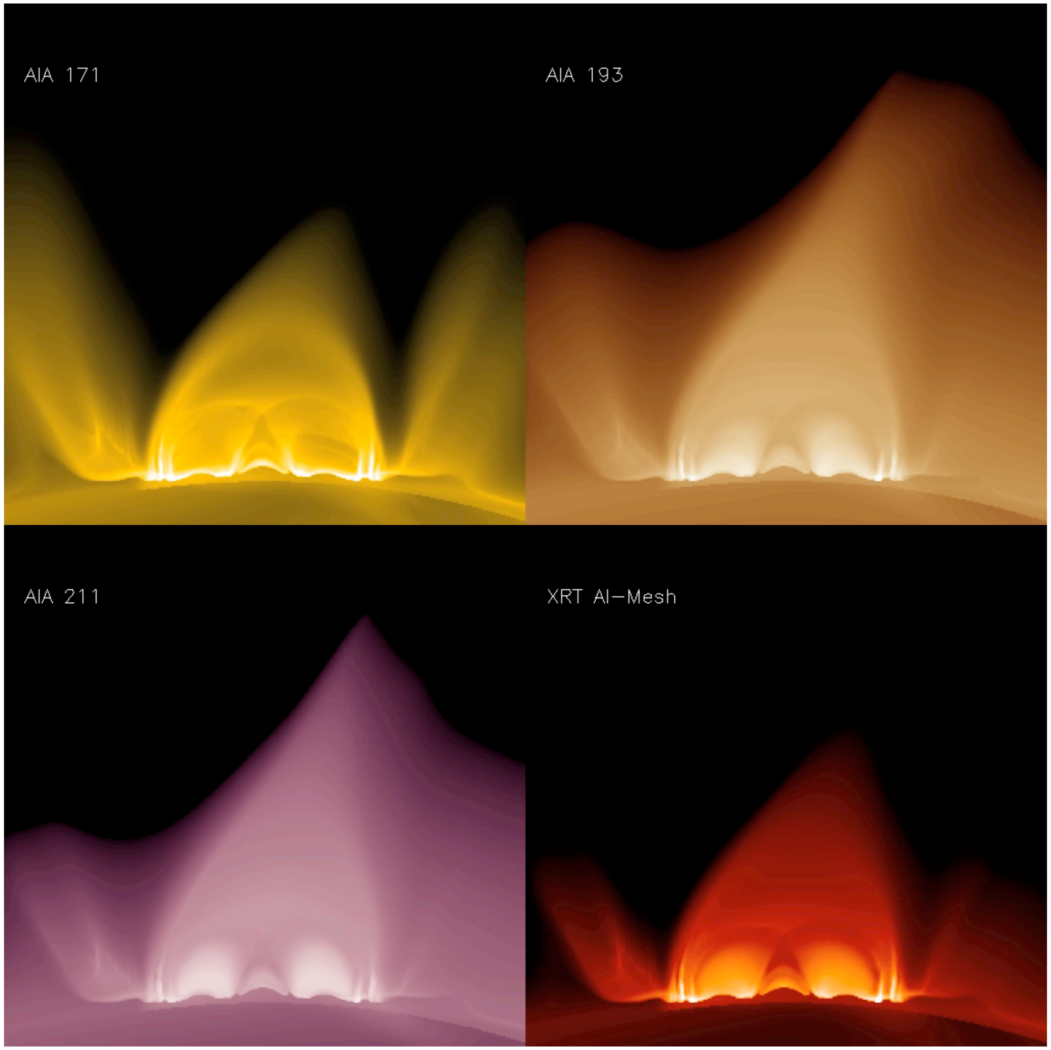
Fast CME: 2 Global Views



- CME slows down as it propagates outward
- Configuration settles afterward
- In this case the configuration is unstable and erupts without an external perturbation

Eruption in simulated AIA emission

- Initial "wave" from imperfect force balance
- Configuration settles afterward
- In this case the configuration is unstable and erupts without an external perturbation



A Configuration-Preserving TD Model

- A problem with the TD model for initiating CMEs is that it significantly perturbs the original photospheric flux distribution
- This may alter the streamer configuration so much that it no longer resembles the observed streamers
- We have been investigating a technique to nearly preserve the observed photospheric flux distribution when inserting the flux rope

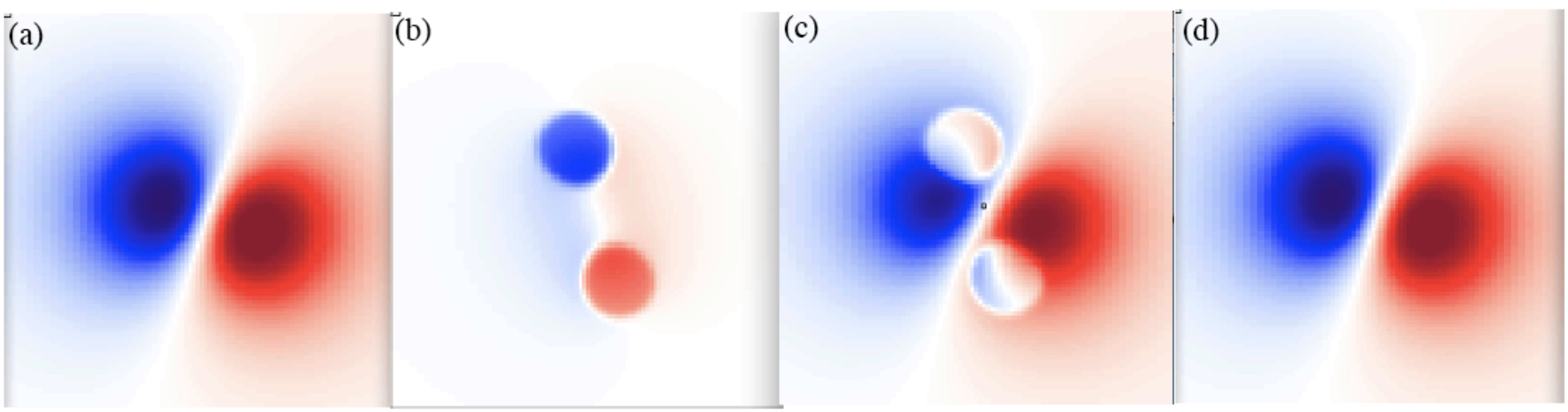
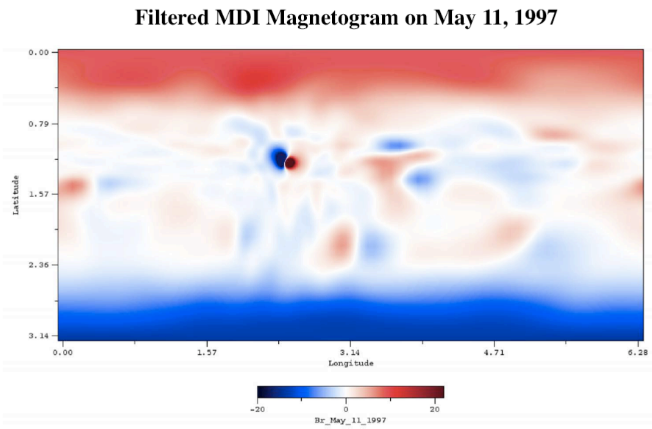
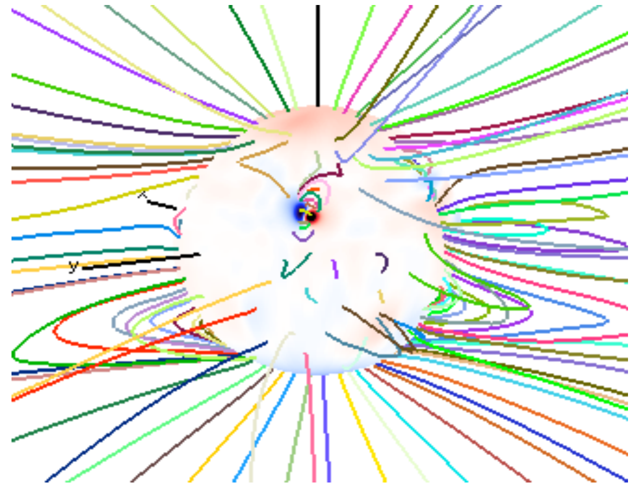
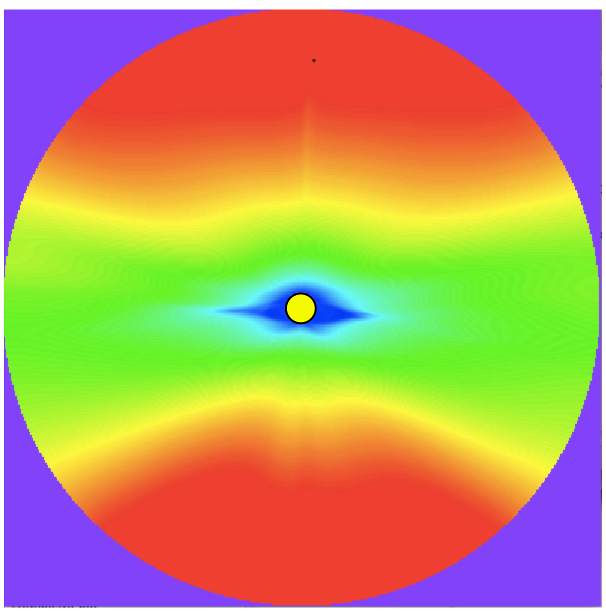


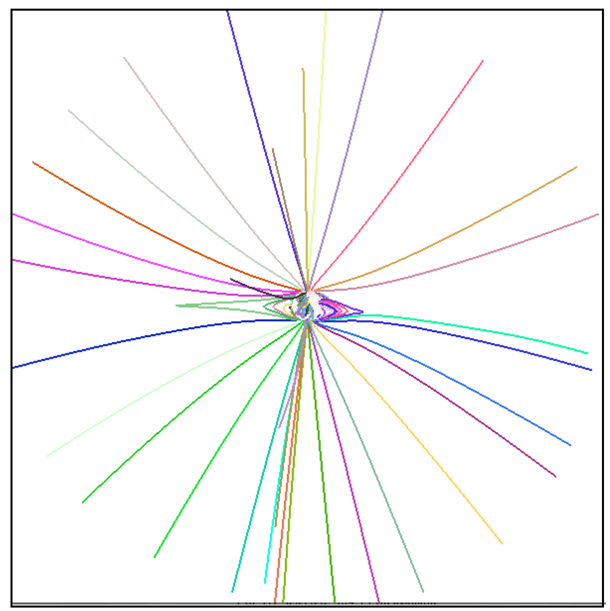
Figure 6. Concept of flux-preserving TD model. (a) Initial magnetic flux at the boundary in the active region. (b) Magnetic Flux for the footprints of the TD flux rope. (c) The magnetic flux in (b) is subtracted from (a) to yield this distribution, the starting point for the MHD calculation. (d) Final magnetic after TD flux rope insertion (same as (a)).

May 1997: Global Coronal Solution to 20 R_S





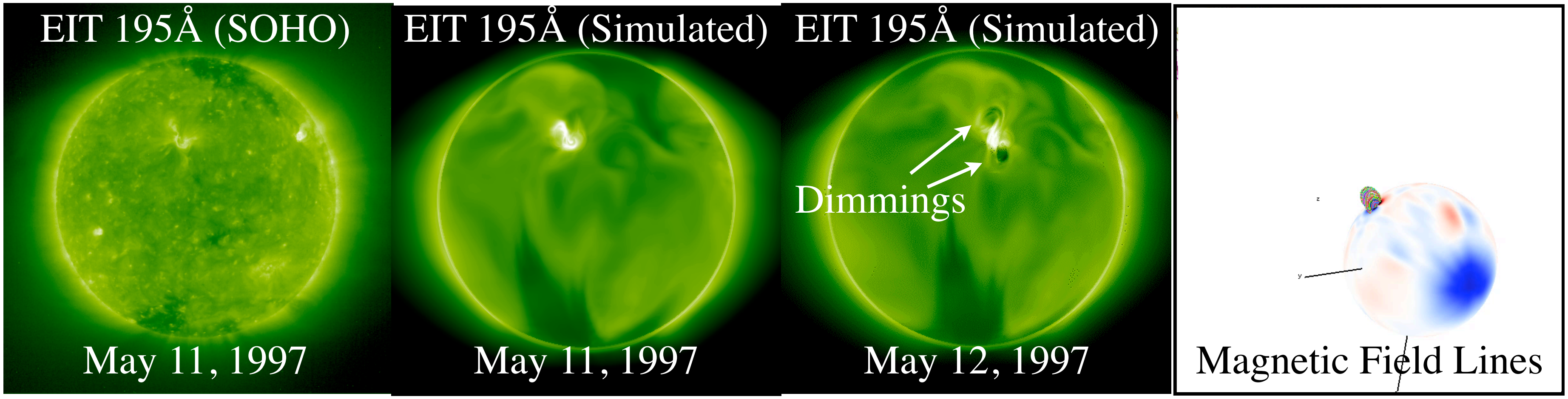




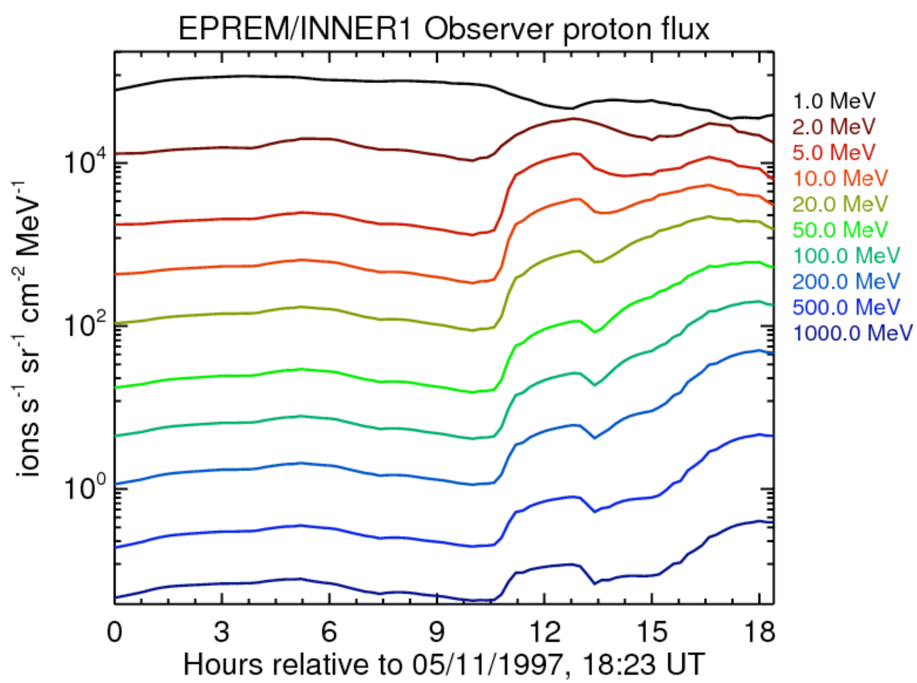
Vr (max ~ 750 km/s)

Magnetic Field Lines

MAS-EPREM Coupling: Preliminary Result



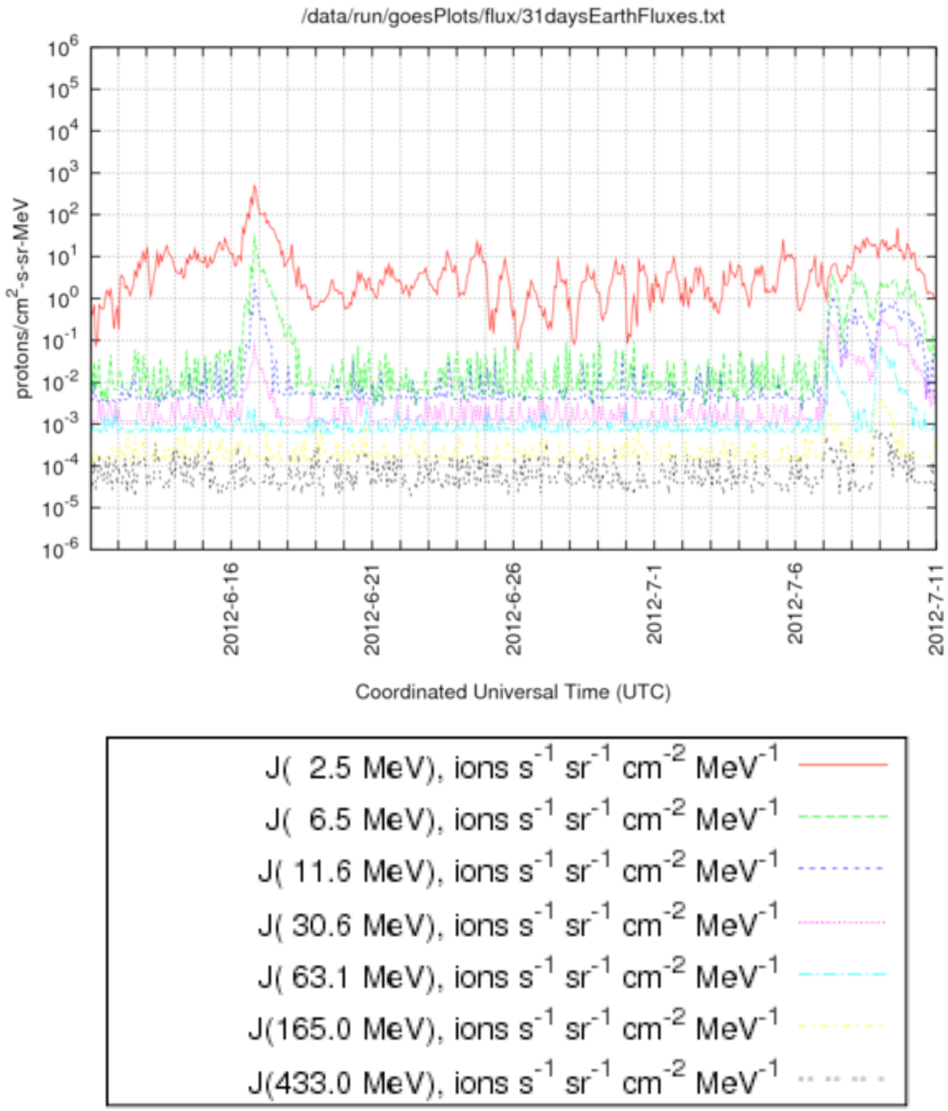
- CME is relatively slow - weak shock formed
- Modest event simulated in EPREM



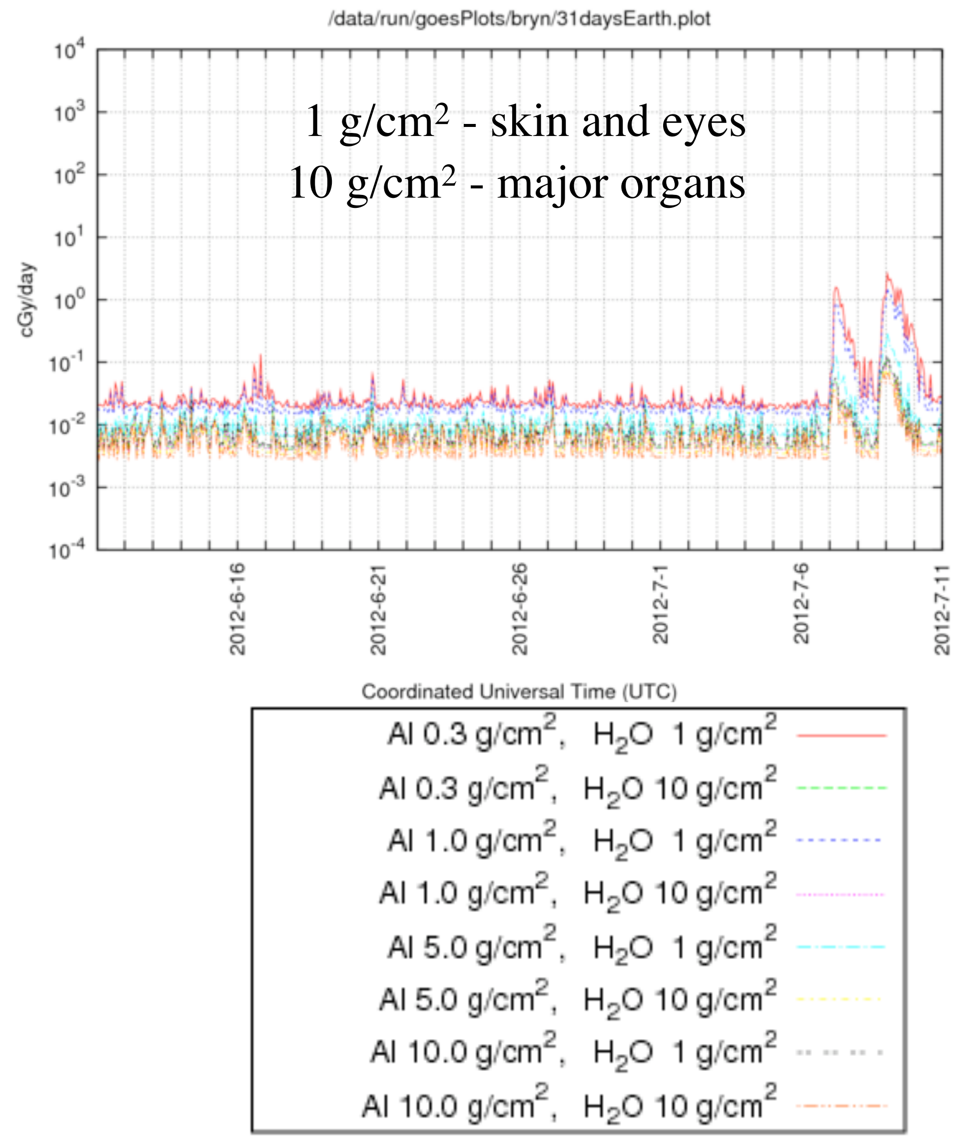
EMMREM: Earth-Moon-Mars Radiation Module

http://emmrem.unh.edu/prediccs.html

Energetic Particle Fluxes at Earth



Doses at 1 AU



Resistive MHD Equations
(Polytropic Model)

$$\nabla \times \mathbf{B} = \frac{4\pi}{c}\mathbf{J}$$

$$\nabla \times \mathbf{E} = -\frac{1}{c}\frac{\partial \mathbf{B}}{\partial t}$$

$$\mathbf{E} + \frac{1}{c}\mathbf{v} \times \mathbf{B} = \eta \mathbf{J}$$

$$\frac{\partial \rho}{\partial t} + \nabla \cdot (\rho \mathbf{v}) = 0$$

$$\rho\left(\frac{\partial \mathbf{v}}{\partial t} + \mathbf{v} \cdot \nabla \mathbf{v}\right) = \frac{1}{c}\mathbf{J} \times \mathbf{B} - \nabla p + \rho \mathbf{g} + \nabla \cdot (\nu \rho \nabla \mathbf{v})$$

$$\frac{\partial p}{\partial t} + \nabla \cdot (p \mathbf{v}) = (\gamma - 1)(-p \nabla \cdot \mathbf{v} + \mathrm{S})$$

$$\gamma = 1.05, \quad \mathrm{S} = \eta \mathrm{J}^2 + \nu \rho \nabla \mathbf{v} : \nabla \mathbf{v}$$ (S frequently neglected)

Energetic Particle Transport and Acceleration: EPREM

- Solves for particle transport along field lines in the Lagrangian grid (Kota, 2007)

$$\left(1-\frac{(\vec{u}\cdot e_b)v\mu}{c^2}\right)\frac{df}{dt}+v\mu\frac{\partial f}{\partial z}+\frac{(1-\mu^2)}{2}\left[v\frac{\partial \ln B}{\partial z}-\frac{2}{v}e_b\cdot\frac{d\vec{u}}{dt}+\mu\frac{d\ln(n^2/B^3)}{dt}\right]\frac{\partial f}{\partial \mu}+$$
$$\left[-\frac{\mu e_b}{v}\cdot\frac{d\vec{u}}{dt}+\mu^2\frac{d\ln(n/B)}{dt}+\frac{(1-\mu^2)}{2}\frac{d\ln B}{dt}\right]\frac{\partial f}{\partial \ln p}=\frac{\partial}{\partial \mu}\left(\frac{D_{\mu\mu}}{2}\frac{\partial f}{\partial \mu}\right)+S$$

- Model also includes perpendicular diffusion and gradient and curvature drift

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Coronal Heating Rate:

$$H(r,\theta,\phi) \qquad [\mathrm{erg/cm^3/s}]$$

Equivalent Heat Flux at $r = R_\circ$:

$$q(\theta,\phi) = \int_{R_\circ}^{\infty} H(r,\theta,\phi) r^2 \, dr / R_\circ^2 \qquad [\mathrm{erg/cm^2/s}]$$

Total Heating Rate:

$$E = \int_0^{2\pi}\int_0^{\pi}\int_{R_\circ}^{\infty} H(r,\theta,\phi) r^2 \sin\theta \, dr d\theta d\phi \qquad [\mathrm{erg/s}]$$

CORONAL HEATING MODEL

Coronal Heating:

$$H = H_{\mathrm{QS+AR}} + H_{\mathrm{NL}} + H_{\mathrm{FW}} + H_{\mathrm{SS}}$$

Quiet Sun and Active Region Heating:

$$H_{\mathrm{QS+AR}} = H_1 \exp\left(-\frac{(r - R_{\mathrm{o}})}{\lambda_1}\right) B_{\mathrm{photo}}\, M(\mathbf{x})$$

$$\lambda_1 = 0.06 R_{\circ},\ \ q \sim 0 - 20 \times 10^5\,\mathrm{erg/cm^2/s},\ \ E = 4.4 \times 10^{27}\,\mathrm{erg/s}$$

$M(\mathbf{x})$ is a mask (1 in closed-field regions, 0 in open-field regions)

Neutral Line Heating:

$$H_{\mathrm{NL}} = H_2 \exp\left(-\frac{(r - R_{\mathrm{o}})}{\lambda_2}\right) B_{\mathrm{photo}} \sin^4 \Theta$$

$$\lambda_2 = 0.03 R_{\circ},\ \ q \sim 0 - 50 \times 10^5\,\mathrm{erg/cm^2/s},\ \ E = 5.3 \times 10^{27}\,\mathrm{erg/s}$$

Θ is the inclination angle of $\mathbf{B}$ to the vertical in the photosphere

Coronal Heating Model

Fast Wind Heating:

$$H_{\rm FW} = H_3 \exp\left(-\frac{(r - R_{\rm o})}{\lambda_3}\right)$$

$$\lambda_3 = 1R_{\rm o},\ \ q = 0.4 \times 10^5\,{\rm erg/cm^2/s},\ \ E = 2.5 \times 10^{27}\,{\rm erg/s}$$

Short-Scale Heating:

$$H_{\rm SS} = H_4 \exp\left(-\frac{(r - R_{\rm o})}{\lambda_4}\right)$$

$$\lambda_4 = 0.03R_{\rm o},\ \ q = 0.6 \times 10^5\,{\rm erg/cm^2/s},\ \ E = 3.6 \times 10^{27}\,{\rm erg/s}$$

Total Heating Rate:

$$q = 1 - 70 \times 10^5\,{\rm erg/cm^2/s},\ \ E = 15.8 \times 10^{27}\,{\rm erg/s}$$

- See Lionello et al., *Ap. J.*, (2009) for a discussion of heating models