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"MAGNETOHYDRODYNAMIC MODELING OF CORONAL EVOLUTION AND DISRUPTION"

NASW-01005

3rd Quarter (1st Year) Progress Report,

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MAGNETOHYDRODYNAMIC MODELING OF CORONAL EVOLUTION AND DISRUPTION

3rd QUARTER (1st YEAR) PROGRESS REPORT:

3/30/02 - 6/29/02

Our progress for the 3rd quarter of 2002 was summarized in an invited review talk on CMEs given by Jon Linker at the Solar Wind X conference. Slides from the talk are attached in the following pages.

Modeling CMEs in the Corona and Solar Wind*

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Pisa, Italy, June 21, 2002

*Supported by NASA and NSF

OUTLINE

1) Introduction
2) Overview of CME initiation models
   a) Types of models
   b) Storage and release models
   c) What we do / do not understand
3) Overview of interplanetary CME models
   a) Types of models
   b) Can interplanetary observations distinguish between CME initiation models?
   c) How well do we understand interplanetary flux ropes?
4) Summary: My guess at the Future

INTRODUCTION

- Coronal Mass Ejections (CMEs) are a fundamental aspect of solar and heliospheric physics.
- Despite many years of study, their origin and evolution is poorly understood:
    - We don't know how CMEs are initiated in the corona.
    - We don't know how they give rise to the structures we observe in interplanetary space.
- Present observations, as well as new observations that will be available in the next few years, give us the opportunity to make significant progress on these problems. Modeling is a key ingredient to success.
- This will be a "narrow" review: I will try to touch on the areas that I believe represent the upcoming challenges in modeling CMEs, and where I think significant advances are likely to be made.

Classification of Models
(Klimchuk 2001)

- **Storage and Release**
  - Energy is stored in the magnetic field over a long period of time (days to weeks), and released as a result of instability, loss of equilibrium, or nonequilibrium (cf., Forbes, JGR, 2001)
- **Directly Driven**
  - Energy is pumped into the corona during eruption
  - A flux rope structure is assumed: can be used to fit white light observations
  - No observational support for vast energy flux into corona at eruption (cf., Forbes, Spring AGU 2001)
- **Thermal Blast**
  - Thermal energy is input in the form of an unspecified energy source (*e.g.*, thermal energy from a flare)
  - Lots of observational problems, currently not in favor

Storage and Release Models

- Energy is stored over a long period and released over a short period
- Instability is a competition between magnetic field tension and magnetic pressure:
- For example, for force-free equilibria:

$$\mathbf{J} \times \mathbf{B} = 0$$

$$(\nabla \times \mathbf{B}) \times \mathbf{B} = 0$$

$$\mathbf{B} \cdot \nabla \mathbf{B} = \frac{1}{2} \nabla B^2$$

- Generally, eruption occurs when field line tension is reduced or when pressure is increased
- There must be free energy ⇔ parallel electric current ⇔ twist ⇔ shear
- Highly nonpotential magnetic structures are in fact frequently observed

HOW IS THE ENERGY STORED?

- Photospheric motions can store energy in the field by twisting/shearing.
- Magnetic fields may emerge already twisted (*i.e.*, carrying current) from below the photosphere.
- Recent studies (e.g., Demoulin et al., 2002) indicate that that the twist in the field primarily emerges with new fields.
- Differential rotation is unlikely to provide the primary energization of the field; smaller scale motions are not yet ruled out.

Storage and Release Models: Examples

- Flux Cancellation Model (*e.g.*, van Ballegooijen & Martens 1989; Forbes & Isenberg 1991; Amari *et al.* 2000; Linker *et al.* 2001)
- Breakout Model (Antiochos, DeVore, & Klimchuk,1999)
- A new model by Zhang and Low postulates that the rough classification of two types of CMEs (fast and slow) are related to "normal" and "inverse" polarity prominences
- It is difficult to distinguish between the models:
  - CME initiation does not produce significant photospheric magnetic field changes
  - In many models, the eruption is a threshold effect (% flux change, critical shear, etc.)
  - Differences between models can be very subtle

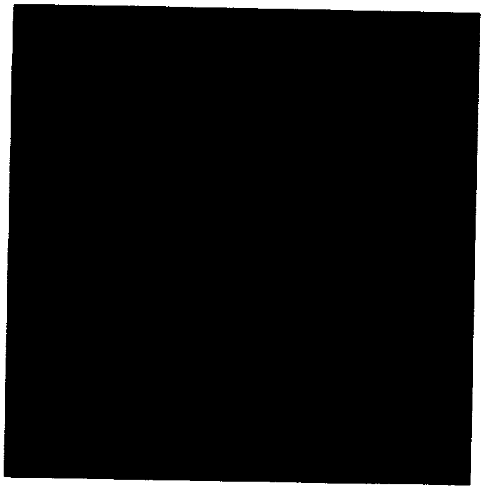
FLUX CANCELLATION MODEL

(*e.g.*, van Ballegooijen & Martens 1989;
Forbes & Isenberg 1991;
Amari *et al.* 2000;
Linker *et al.* 2001)

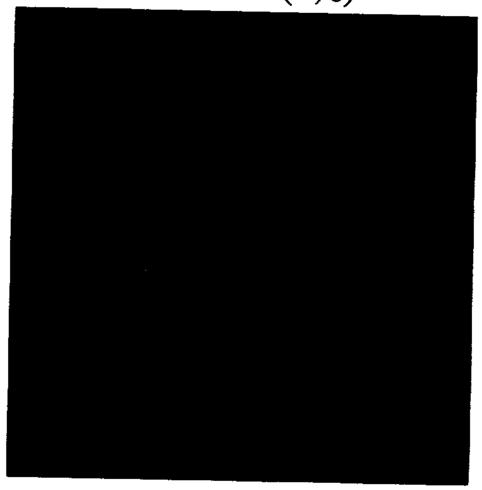
- Flux cancellation at the neutral line can destabilize a sheared arcade
- Flows that converge toward the neutral line can lead to flux cancellation (van Ballegooijen & Martens 1989)
- A flux rope forms above the neutral line
- The dips in the magnetic field lines can support prominence material
- This mechanism produces an energetic eruption with significant conversion of stored magnetic energy into kinetic energy
- There is a threshold for eruption: emergence of less flux than the threshold leads to the formation of a stable filament
- Even a small amount of emerged flux can trigger an eruption
- Dispersal of the magnetic flux in an active region can provide the necessary trigger

Eruption of a Helmet Streamer By Emerging Flux

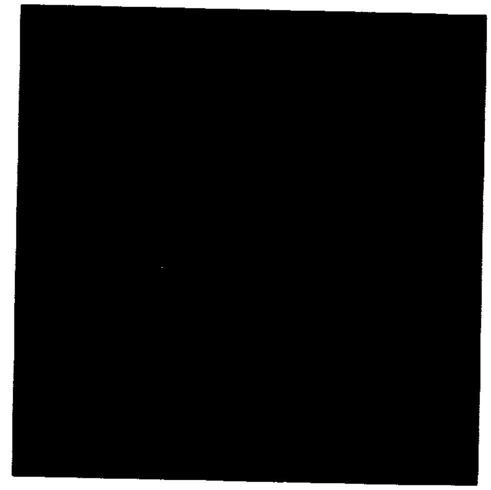
Flux $\Psi(r,z)$



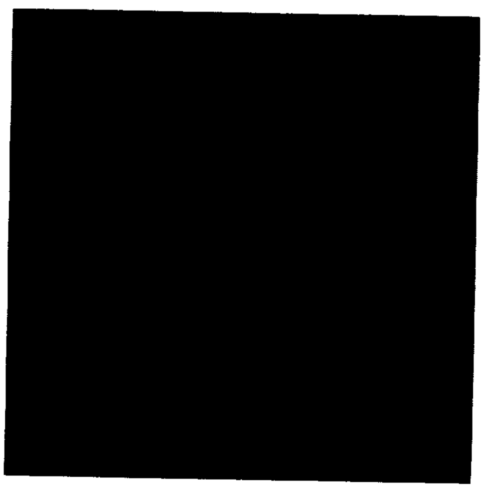
Unsheared streamer



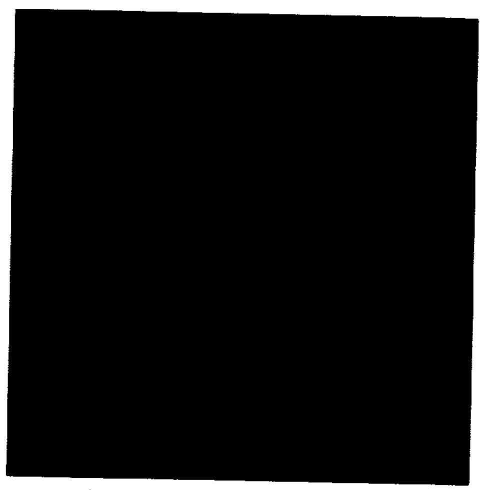
Sheared streamer
$t = t_0$



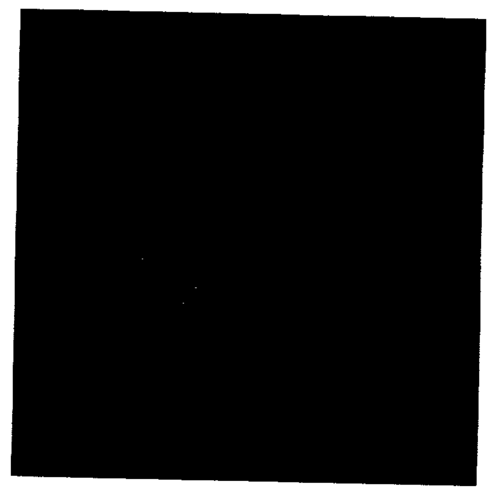
4.5% emerged flux
$t = t_0 + 6$ **hours**



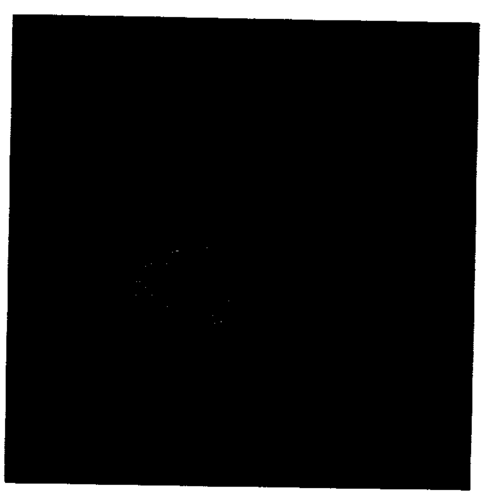
7.5% emerged flux
$t = t_0 + 10$ **hours**



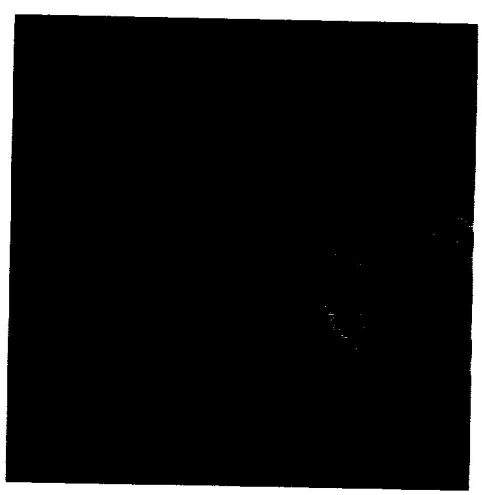
10.5% emerged flux
$t = t_0 + 14$ **hours**



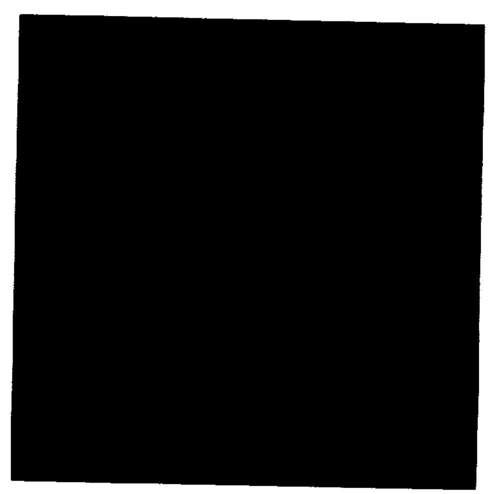
12% emerged flux
$t = t_0 + 16$ **hours**



13.5% emerged flux
$t = t_0 + 18$ **hours**



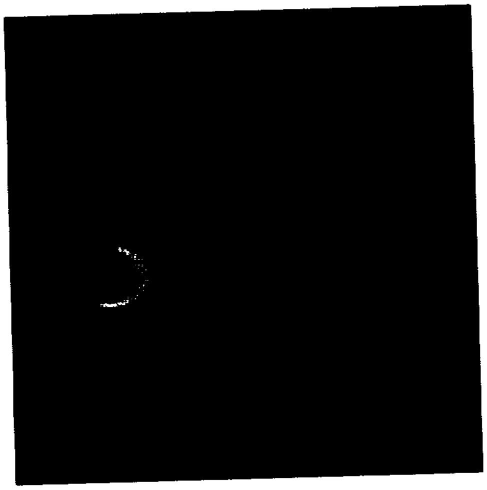
15% emerged flux
$t = t_0 + 20$ **hours**



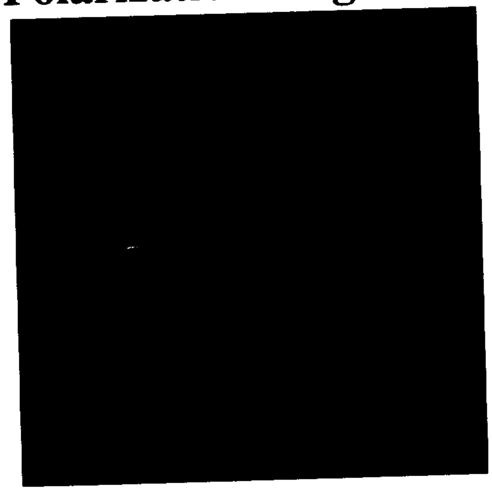
15% emerged flux
$t = t_0 + 2.5$ **days**

Eruption of a Helmet Streamer By Emerging Flux

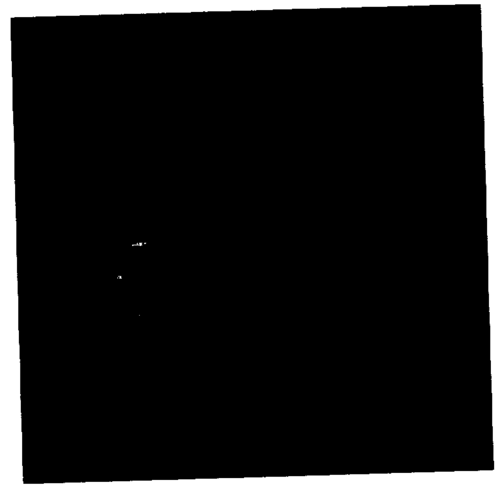
Polarization Brightness



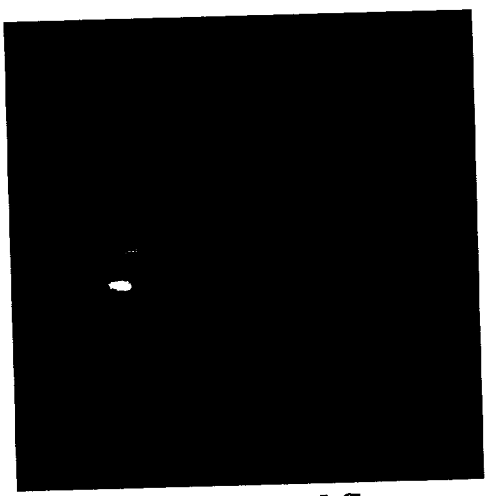
Unsheared streamer



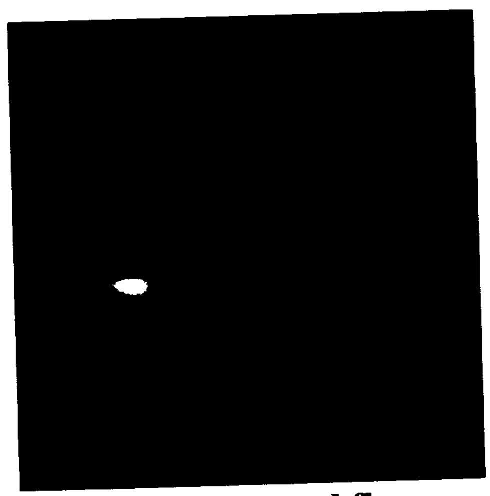
Sheared streamer
$t = t_0$



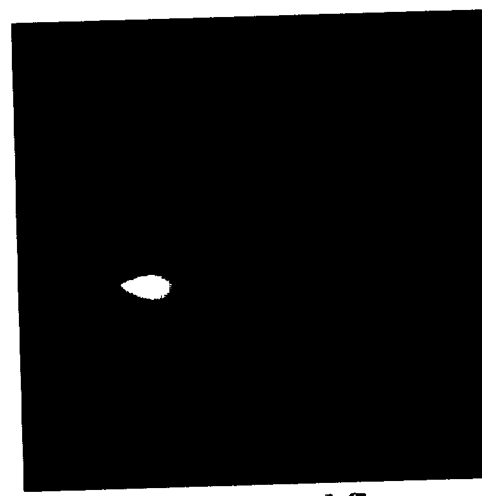
4.5% emerged flux
$t = t_0$ + 6 hours



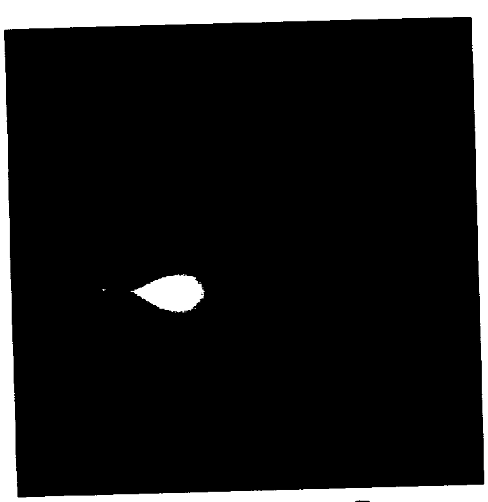
7.5% emerged flux
$t = t_0$ + 10 hours



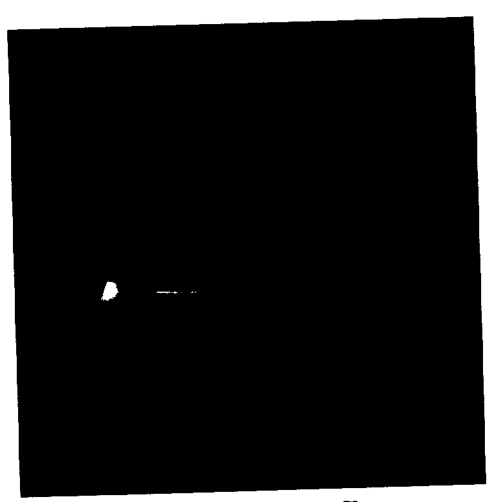
10.5% emerged flux
$t = t_0$ + 14 hours



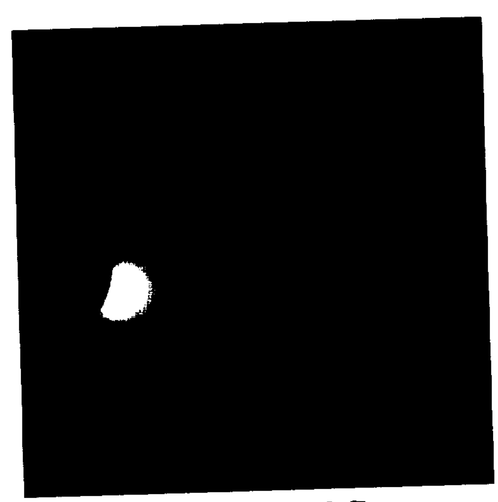
12% emerged flux
$t = t_0$ + 16 hours



13.5% emerged flux
$t = t_0$ + 18 hours



15% emerged flux
$t = t_0$ + 20 hours



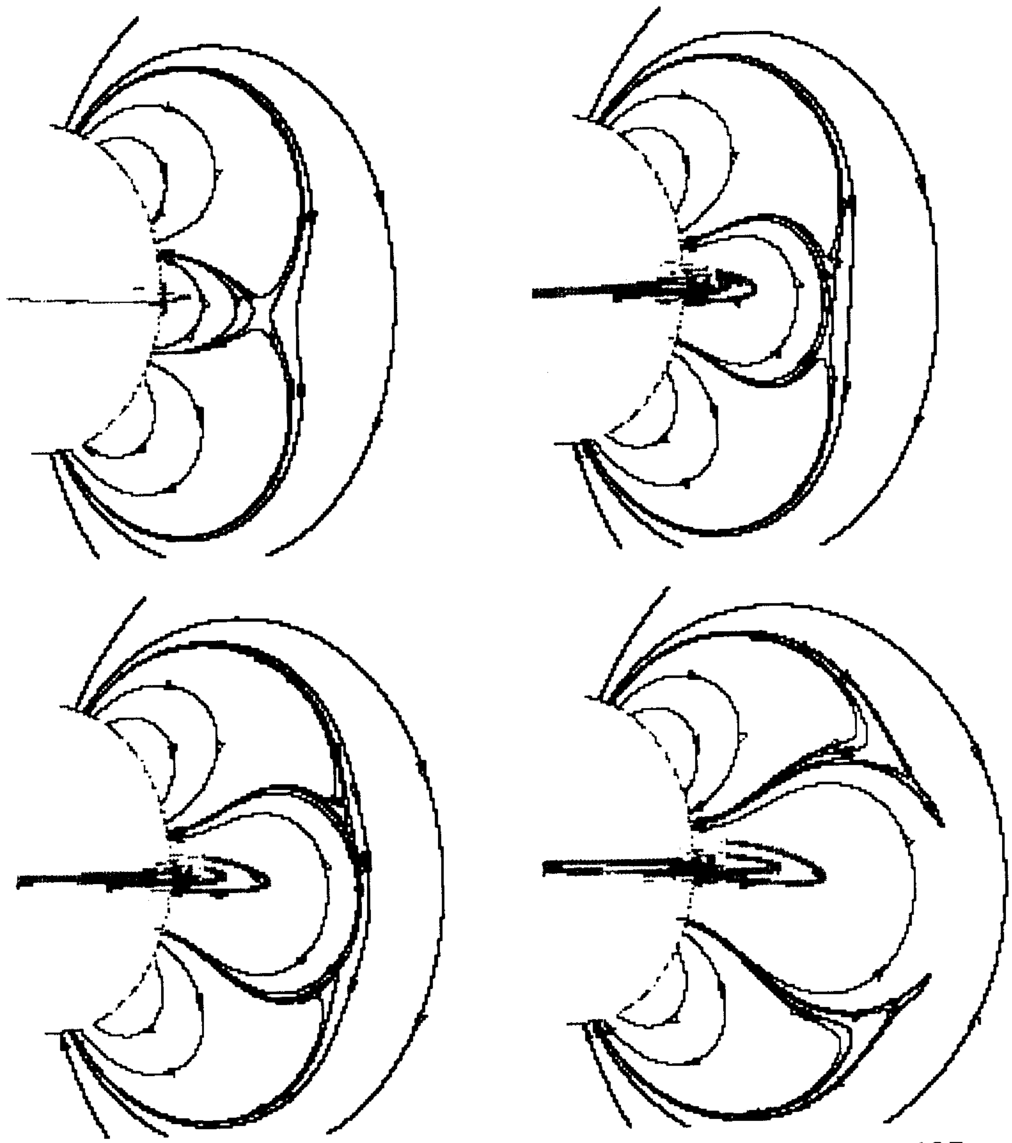
15% emerged flux
$t = t_0$ + 2.5 days

Breakout Model

(Antiochos, DeVore, & Klimchuk 1999, *Ap. J.*, **510**, 485.)

- Requires a more complex magnetic field topology than a simple bipolar magnetic field
- Driven by increasing shear near the neutral line
- Eruption occurs when overlying magnetic field lines reconnect at an X-point, releasing the downward tension force

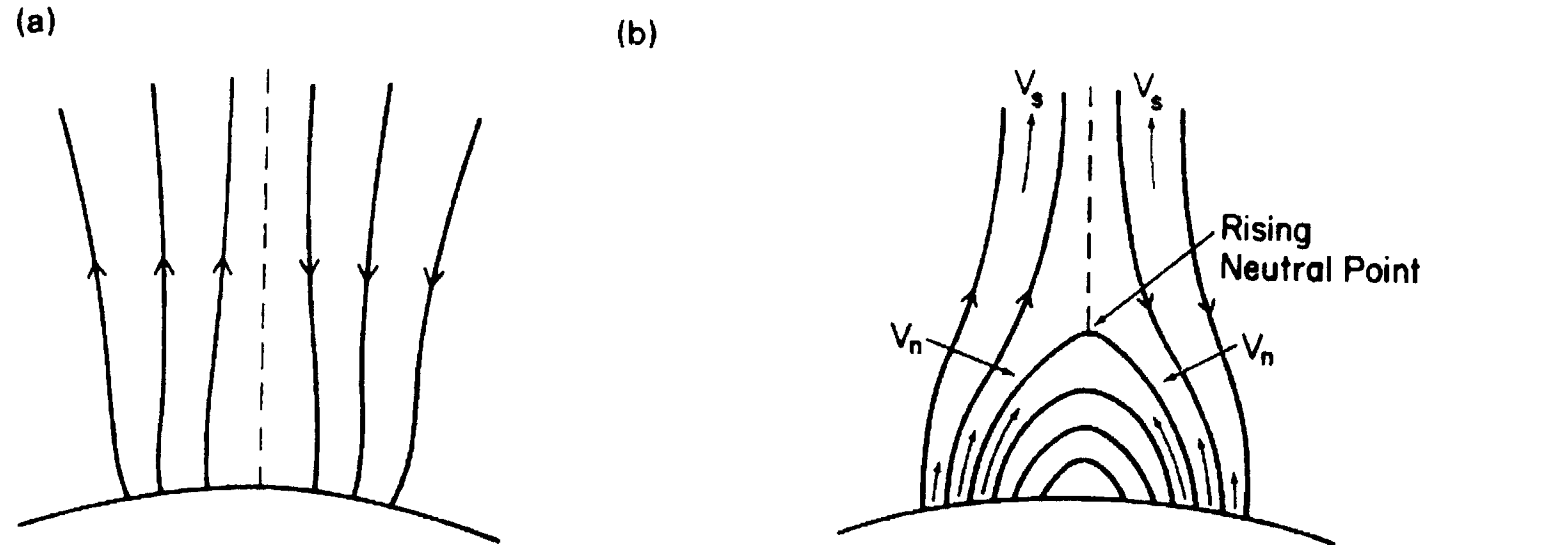
The "Breakout" Model



(Antiochos, DeVore, & Klimchuk 1999, *Ap. J.*, **510**, 485;
Klimchuk 2001, Proc. Chapman Conf. on Space Weather, to appear)

What Do We Think We Understand about CMEs?

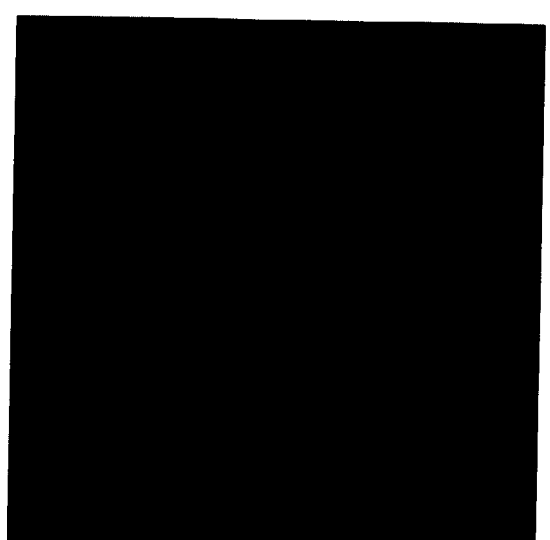
Kopp and Pneuman (1976) - "Post-Flare" Loops Formed From Reconnection



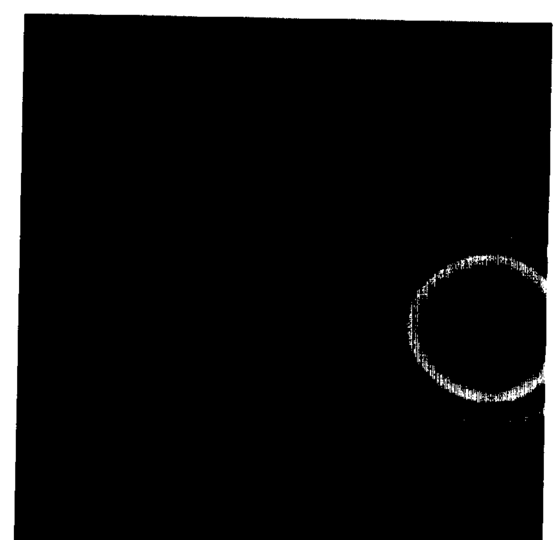
OPEN FIELD LINES AFTER TRANSIENT

SUBSEQUENT RECONNECTION WITH CAPTURE OF MATERIAL ON CLOSED FIELD LINES

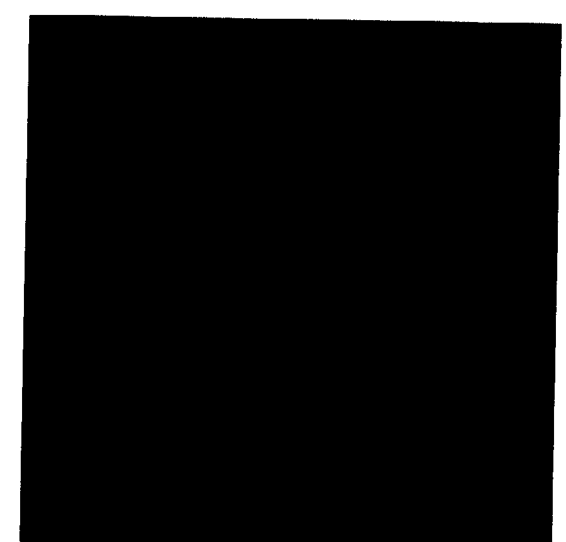
MHD Simulation of Streamer Disruption:



Equilibrium Streamer

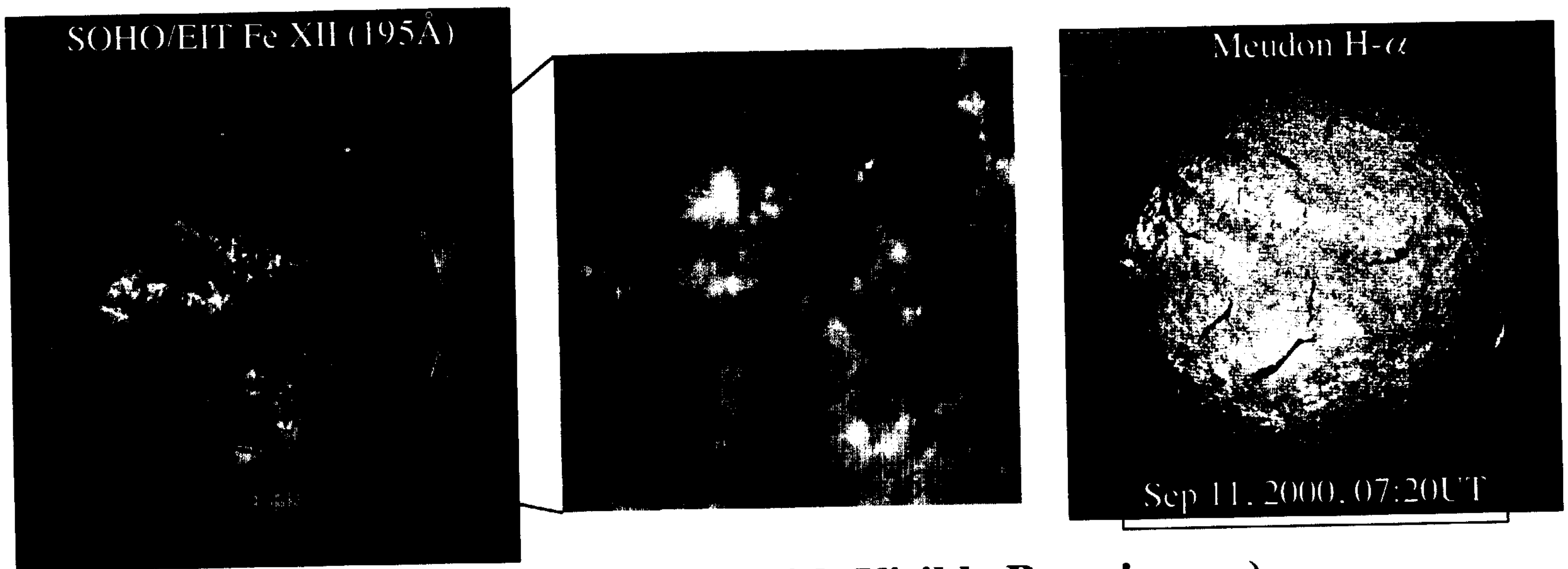


4 Hours After Eruption

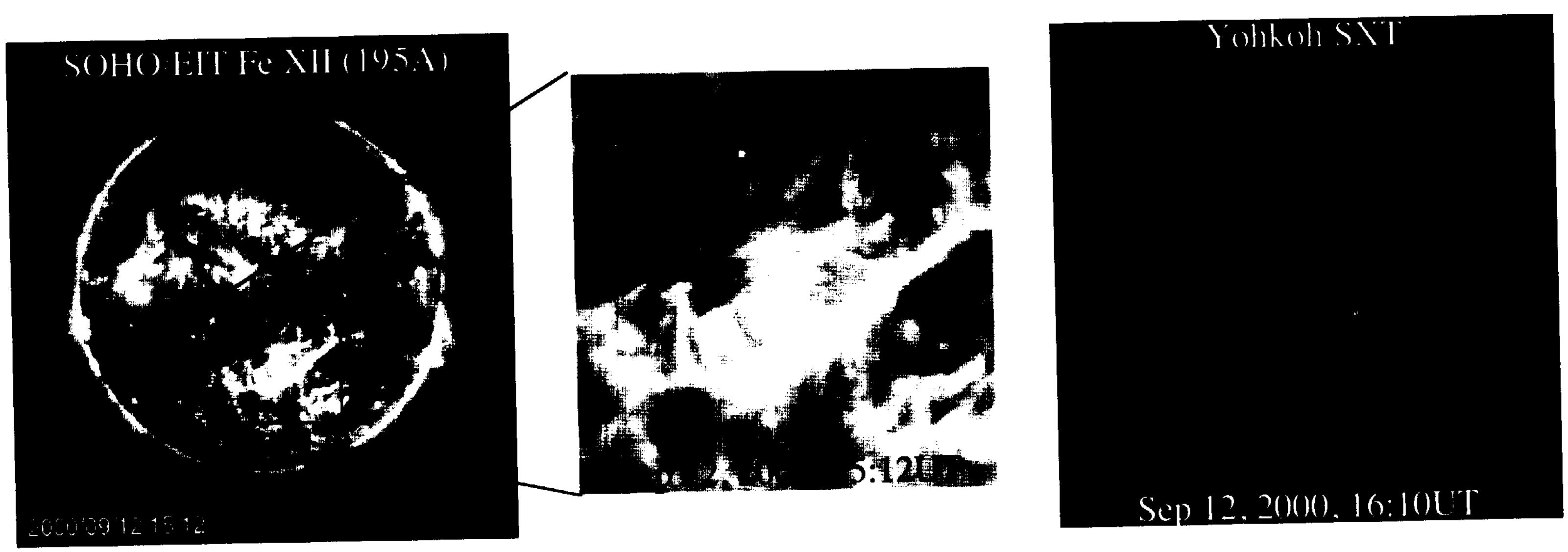


2 days After Eruption

Reconnection in the Aftermath of a CME/Prominence Eruption: Post-“flare” Loops



Pre-Eruption State (With Visible Prominence)



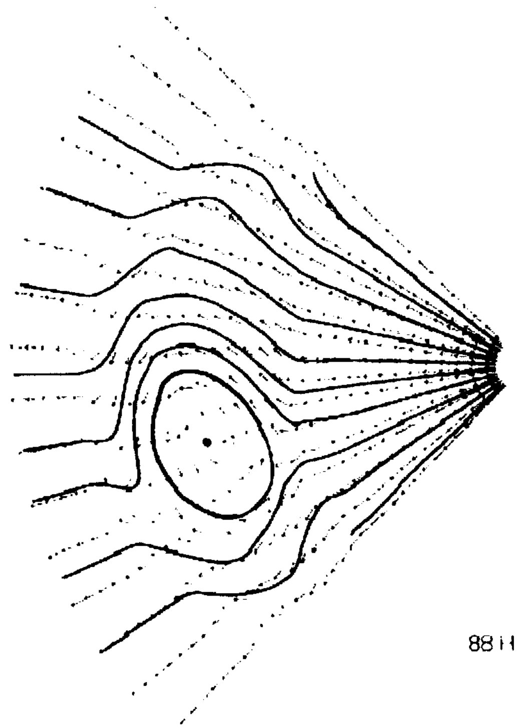
Post-Eruption State

Play Movie ▶

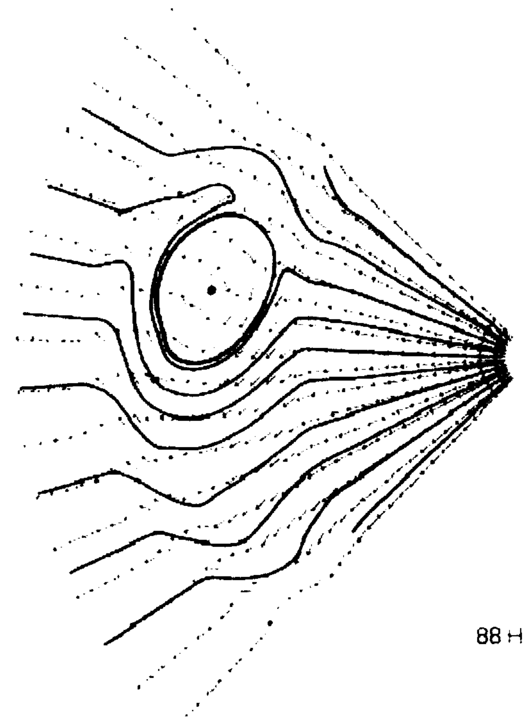
INTERPLANETARY CONSEQUENCES

- Tremendous amount of literature on modeling flux ropes in interplanetary space (e.g., Bothmer, Burlaga, Marubashi, Osherovich, Rust)
- Computing CME evolution: It easiest to start beyond the critical points ($\geq 20\ R_s$)
- Earliest work focused on interplanetary shock waves: Dryer, Wu, and co-workers
- Propagation of "spheromaks" and cylinderical flux ropes(Detman, Vandas, Odstrcil, Cargill; Recent work by Manchester et al. starting in the corona)
- How do ejecta evolve in a structured solar wind? (Odstrcil, Pizzo).
- To make the connection to eruptions seen on the Sun, we must model the CME initiation and evolution from the Sun out into the heliosphere
- Can interplanetary observations give clues to the initiation process?

From Vandas et al. (1996)



case 2a



case 2b

2D Simulation of the Propagation of Cylindrical Flux Ropes in the Solar Wind

Interplanetary Flux Ropes Arise in Competing CME Models

- Mere presence of a flux rope is not a discriminator (different models create a flux rope prior to eruption, or in the aftermath of the eruption)
- More detailed simulations that predict more specific properties might provide discriminators (e.g., heating, composition)

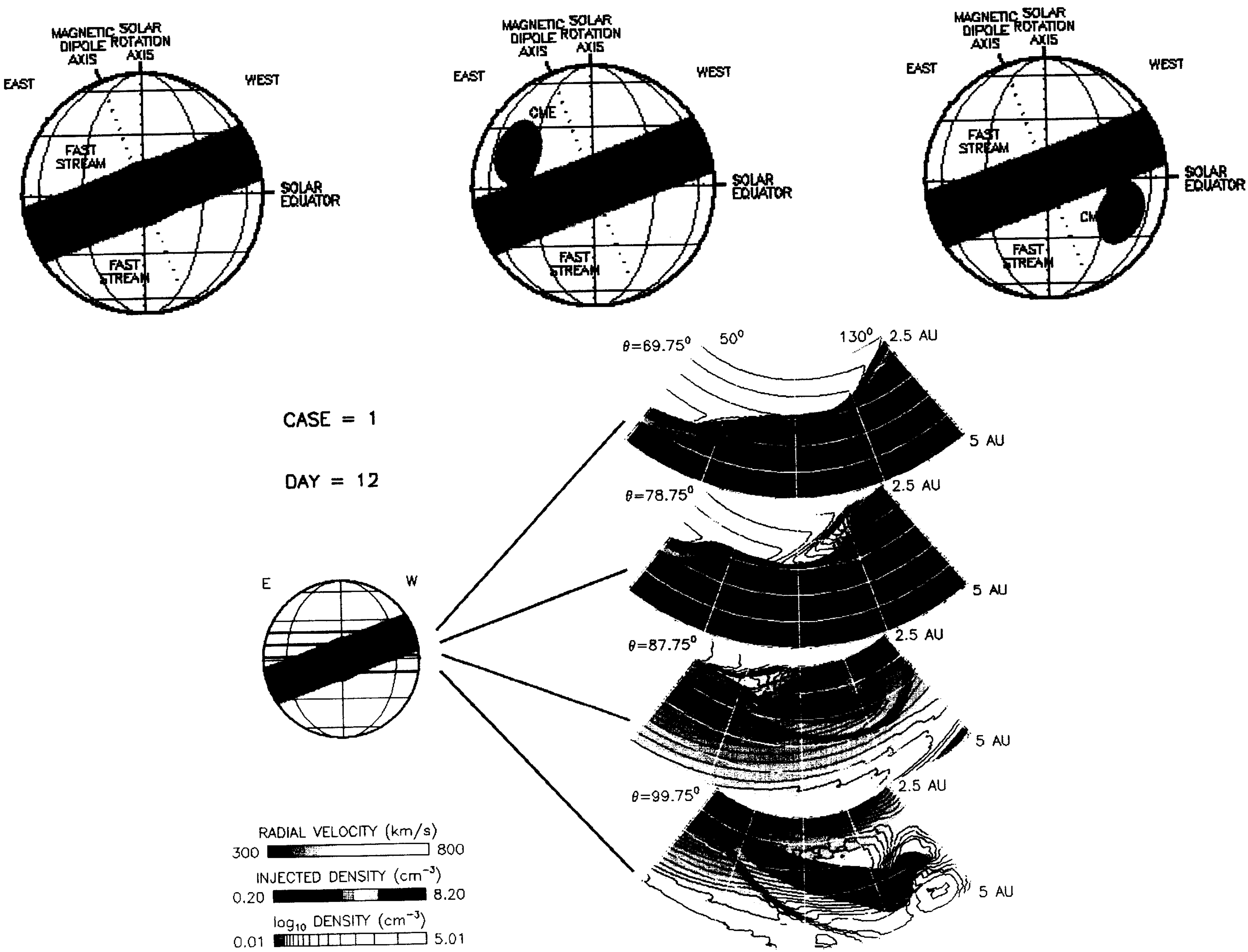
How well do we understand the interplanetary flux ropes we see?

- Interplanetary flux ropes are fit quite successfully with linear force-free field models: $(\nabla \times \mathbf{B}) \times \mathbf{B} = 0$ **or**

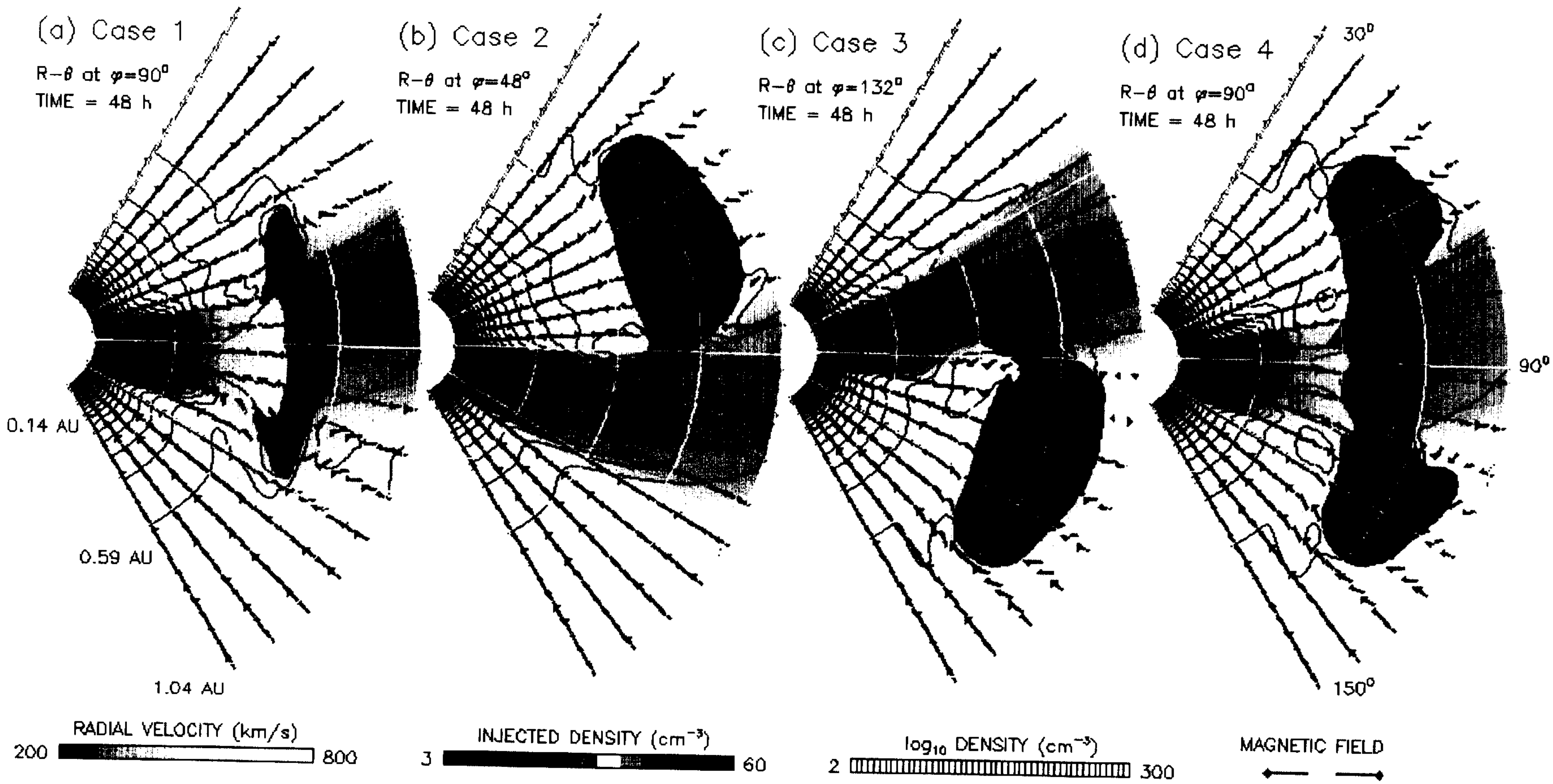
$$(\nabla \times \mathbf{B}) = \alpha B$$

- α = constant is a major simplifying assumption
- Analyzing simulated CMEs can give us insight into the strengths and weakness of force-free models

Propagation of an Idealized Pulse in a Structured Solar Wind
Odstrcil and Pizzo (1999ab)



From Odstrcil & Pizzo (1999)

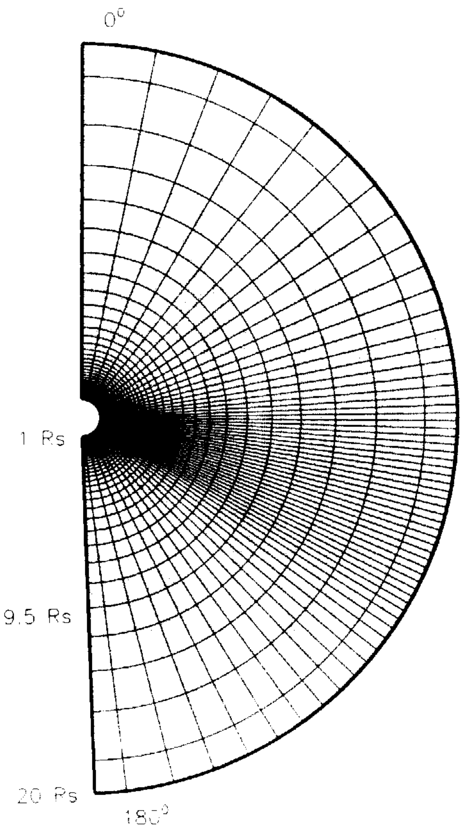


3D MHD Simulation of CME Propagation: Distortion of the Interplanetary Magnetic Field

ISWM

Merged Numerical Grids

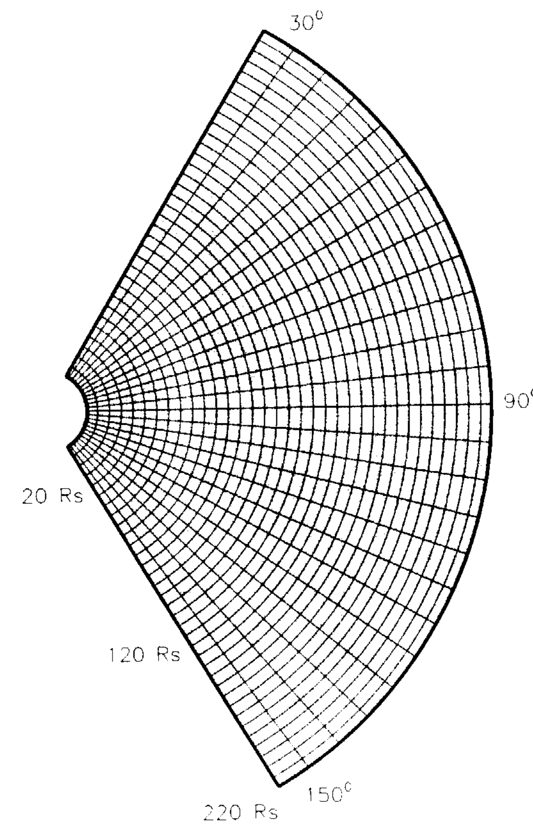
Coronal Model (1 Rs - 20 Rs)



SAIC (San Diego, CA): 200x300 grid points
$\Delta r = 0.0053\text{-}0.59$ Rs, $\Delta\theta = 0.24\text{-}2.4^0$

NOTE: Only every 5th grid line is shown

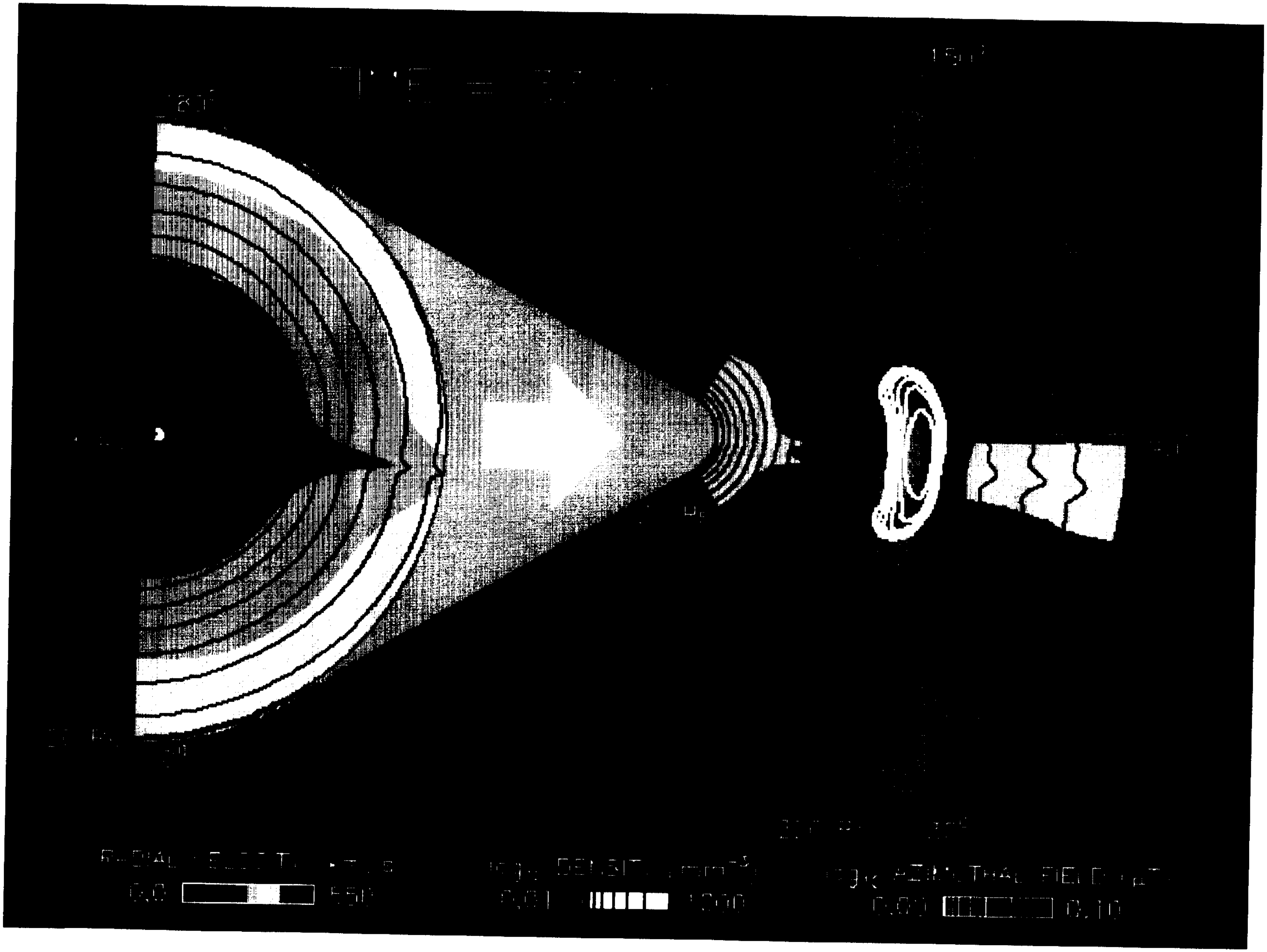
Heliospheric Model (20 Rs - 220 Rs)



CIRES/SEC (Boulder, CO): 340x240 grid points
$\Delta r = 0.5$ Rs, $\Delta\theta = 0.5^0$

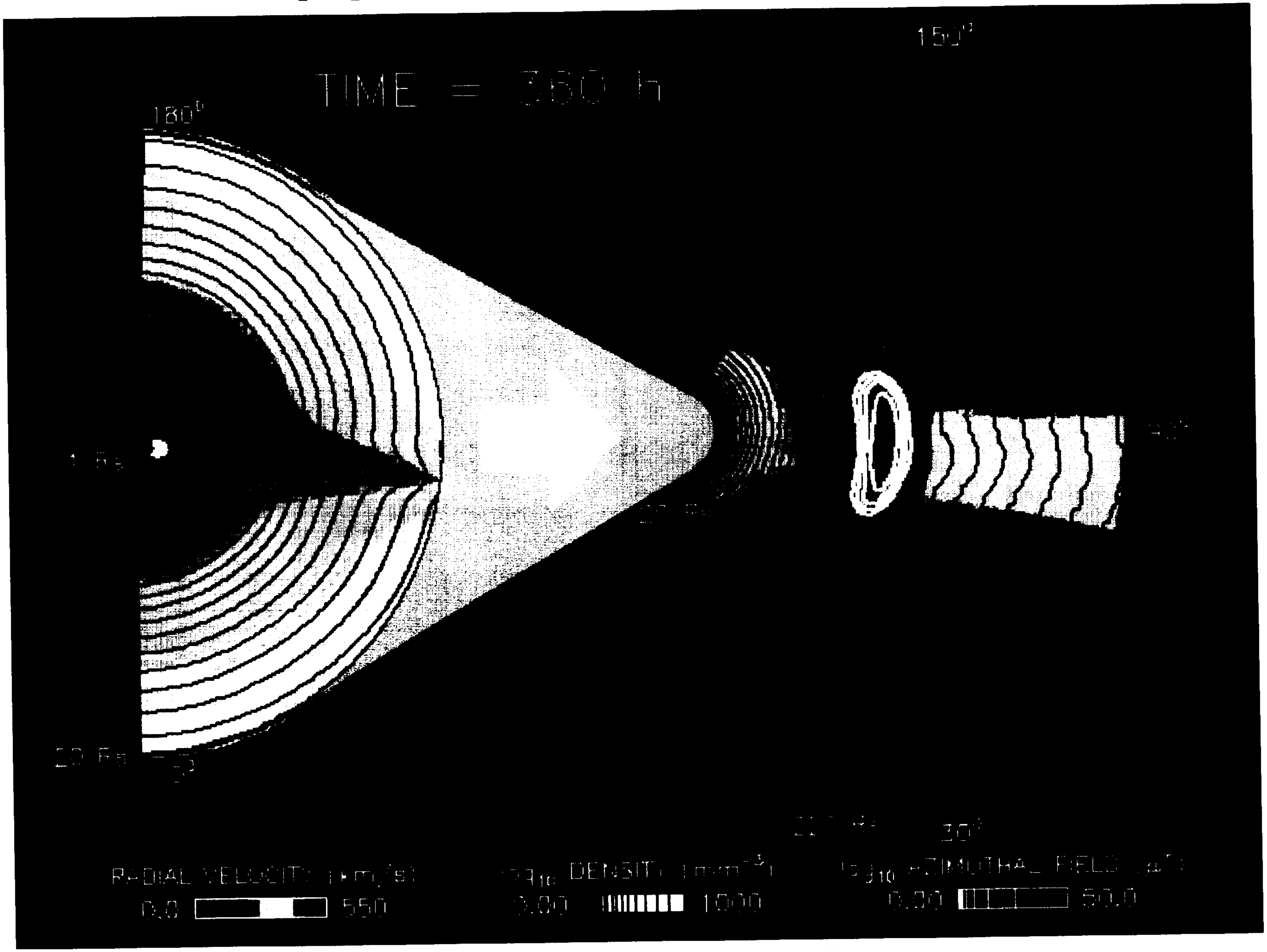
NOTE: Only every 10th grid line is shown

2D Simulation of CME propagation from the Sun to 1 A.U.: Flux Cancellation



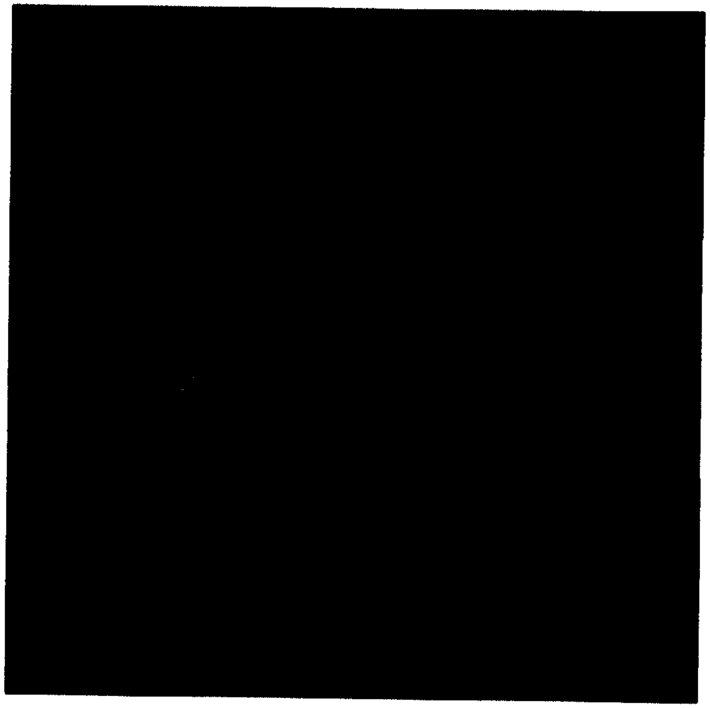
Flux Rope Forms Prior to Eruption

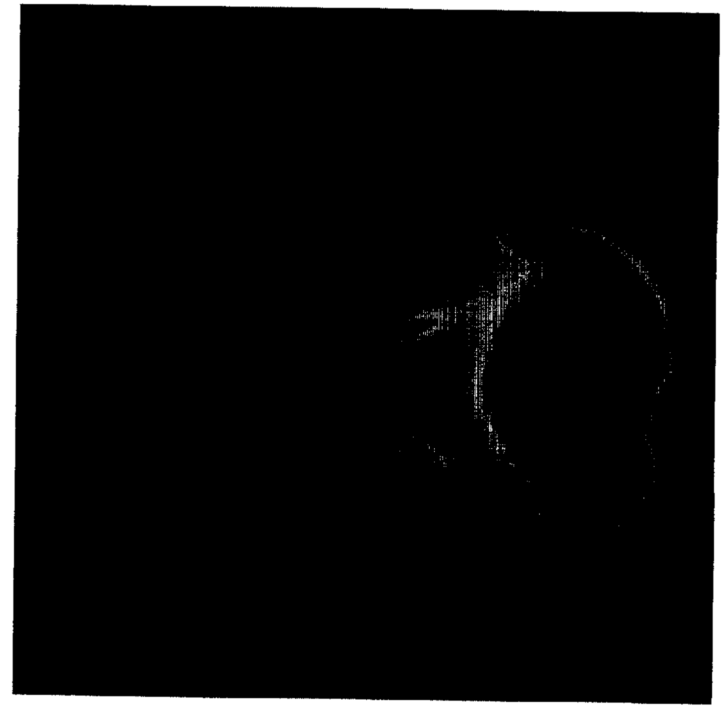
2D Simulation of CME propagation from the Sun to 1 A.U.: Photospheric Shearing Flows



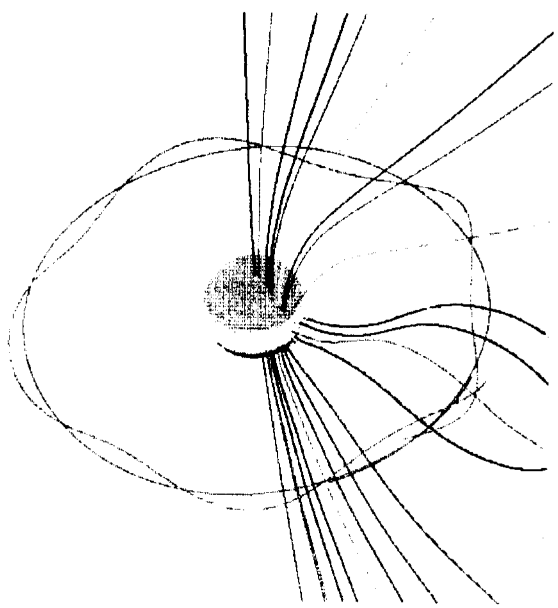
Flux Rope Forms after Eruption

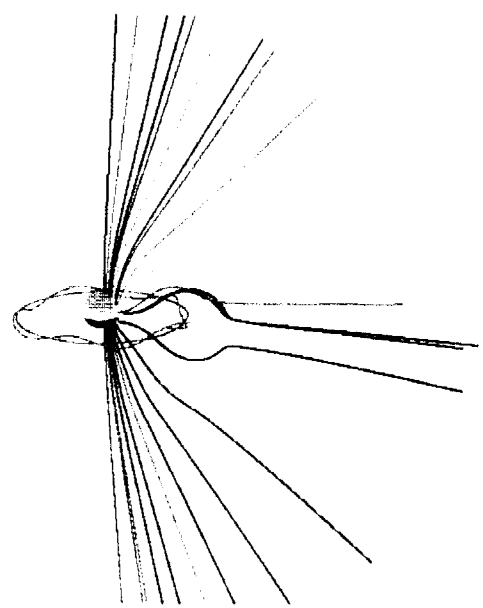
CME Evolution: Near Sun

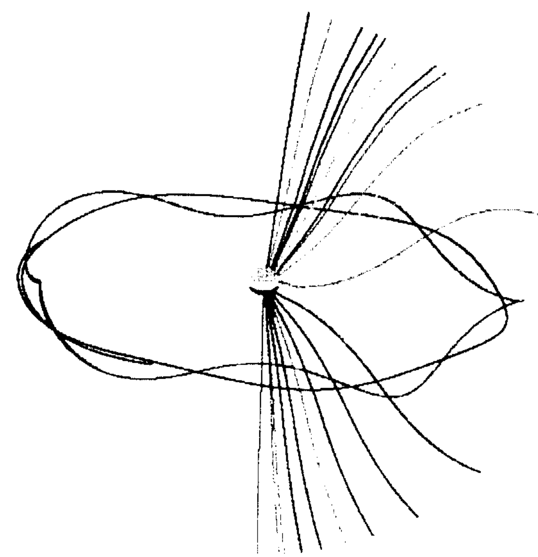




α (= $\mathbf{J}\cdot\mathbf{B}/\mathbf{B}\cdot\mathbf{B}$) evolution, scaled by αL

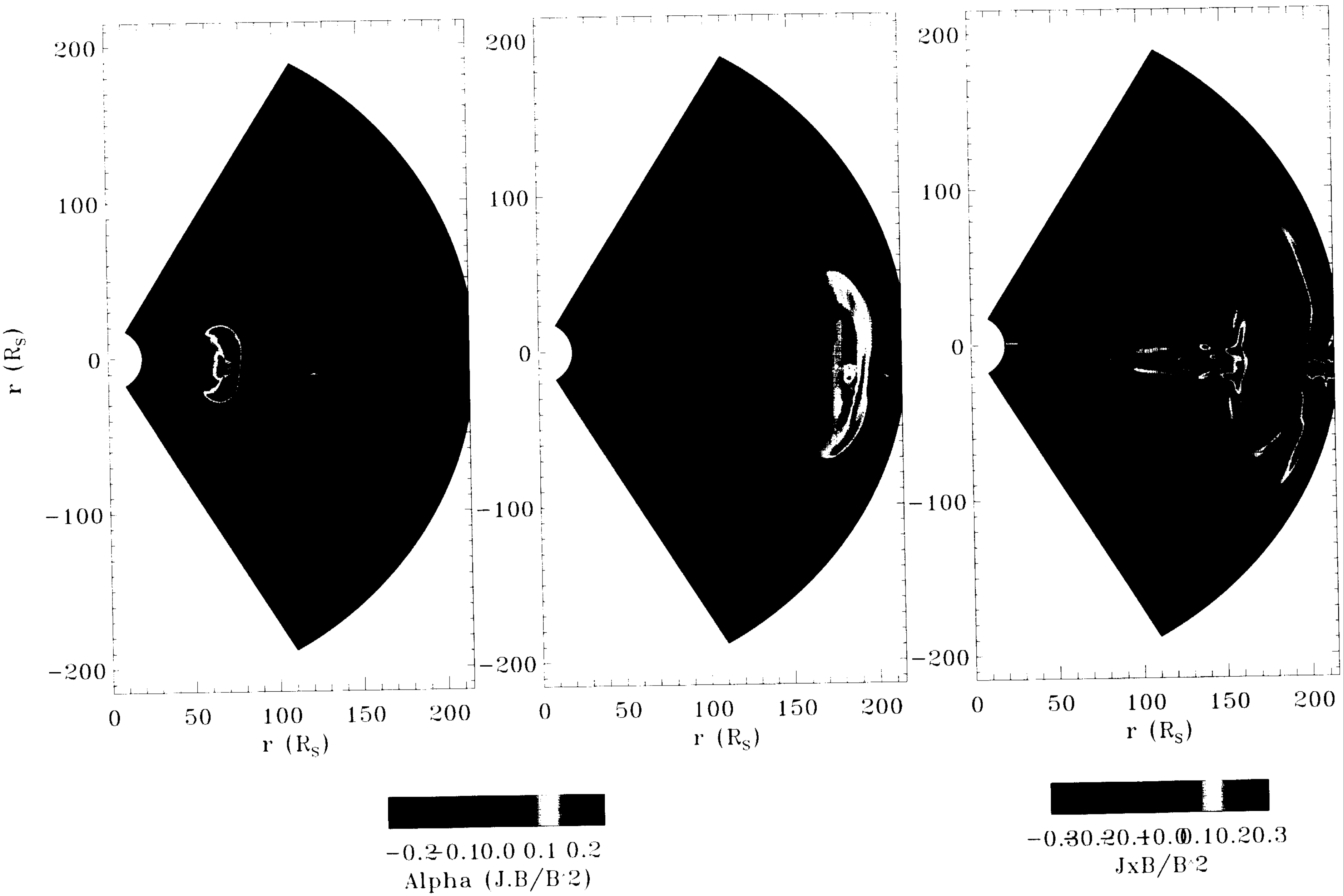


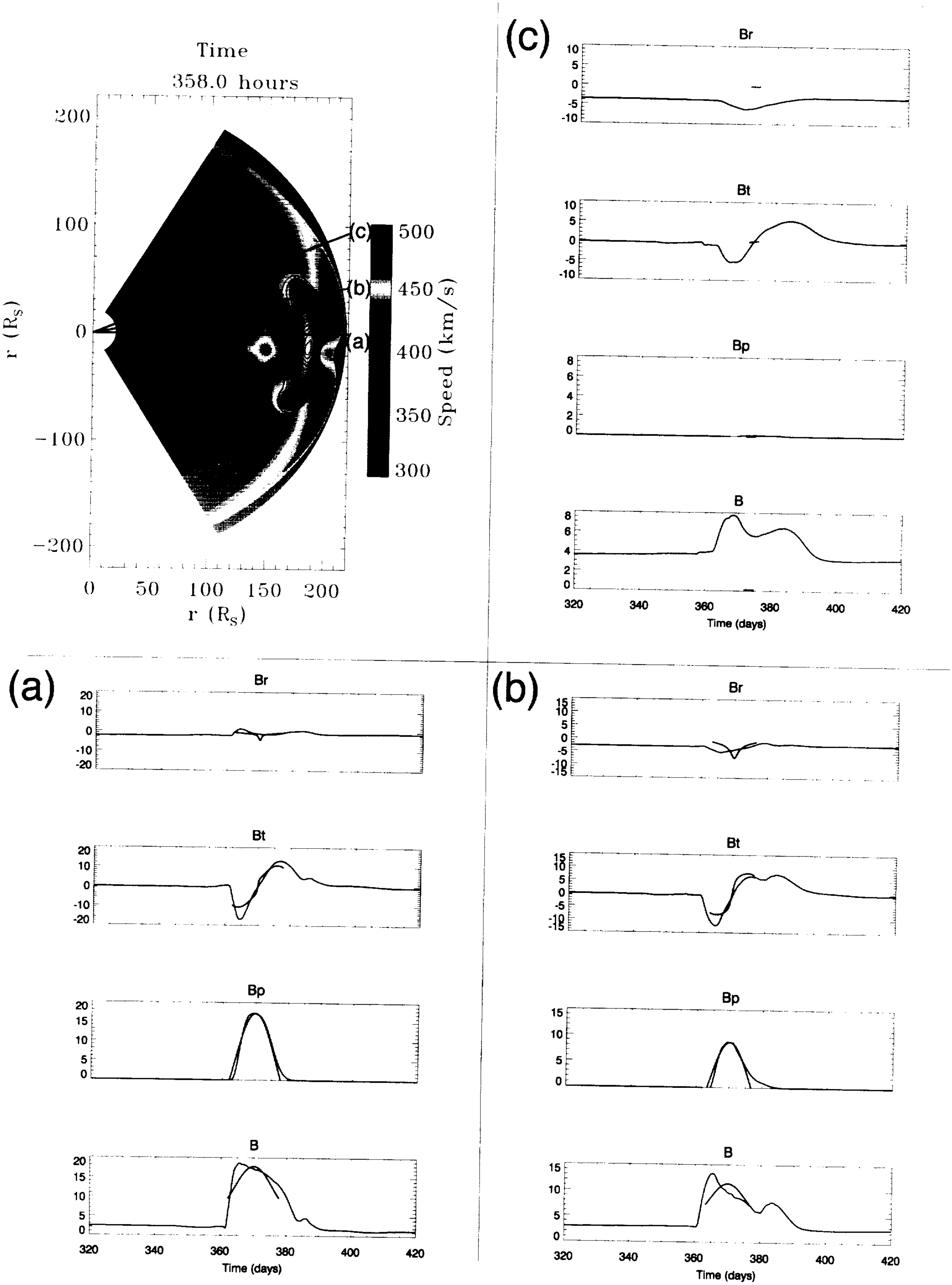




Flux rope field lines

α Evolution to 1 A.U.

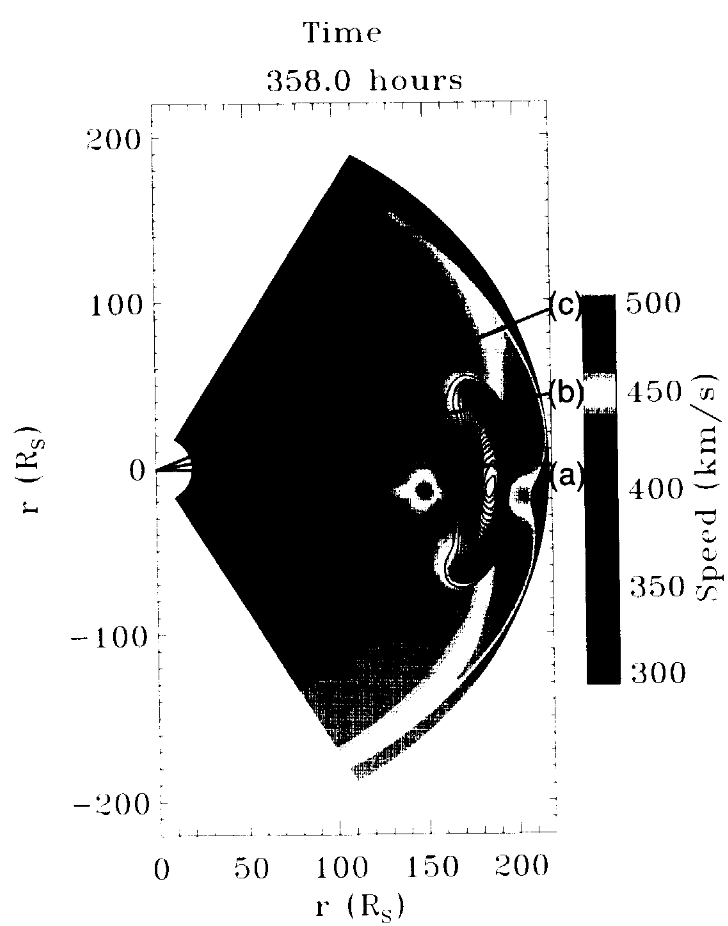


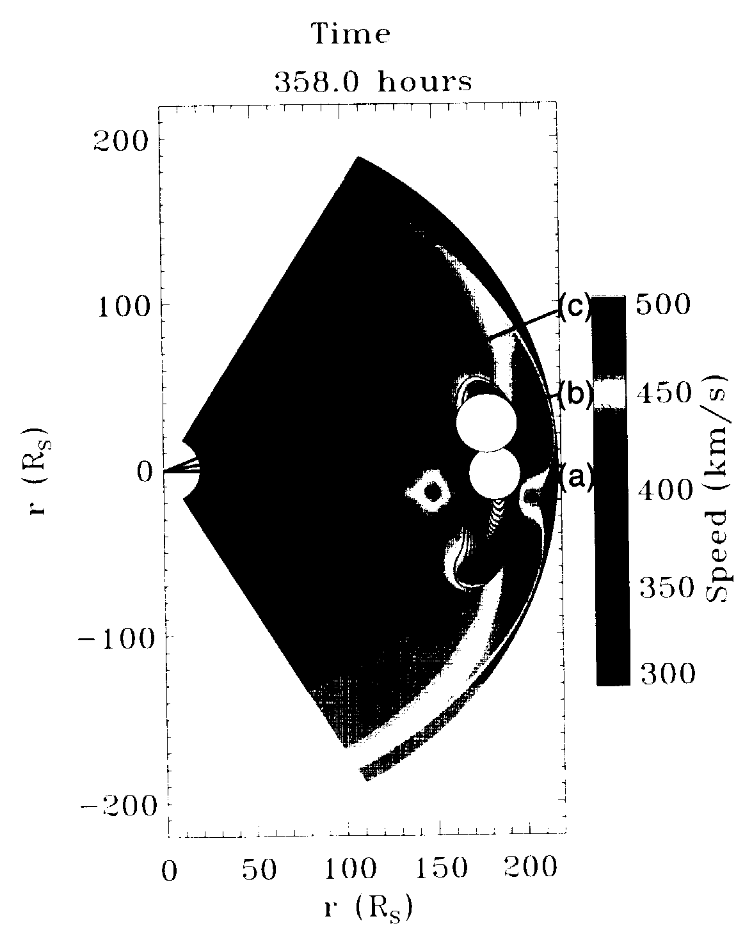

Time
358.0 hours
r (R_S)
(a)
(b)
(c)
Speed (km/s)
500
450
400
350
300
(a)
Br
Bt
Bp
B
Time (days)
(b)
Br
Bt
Bp
B
Time (days)
(c)
Br
Bt
Bp
B
Time (days)

Linear Force Free Fit Assuming Cylindrical Flux Rope:

Impact parameter p:
(a) p = .21R, R=30R_S
(b) p = .54R, R=36R_S
(c) p = 1 (does not encounter flux rope)

Inferred Flux Rope Shape and Size are Misleading

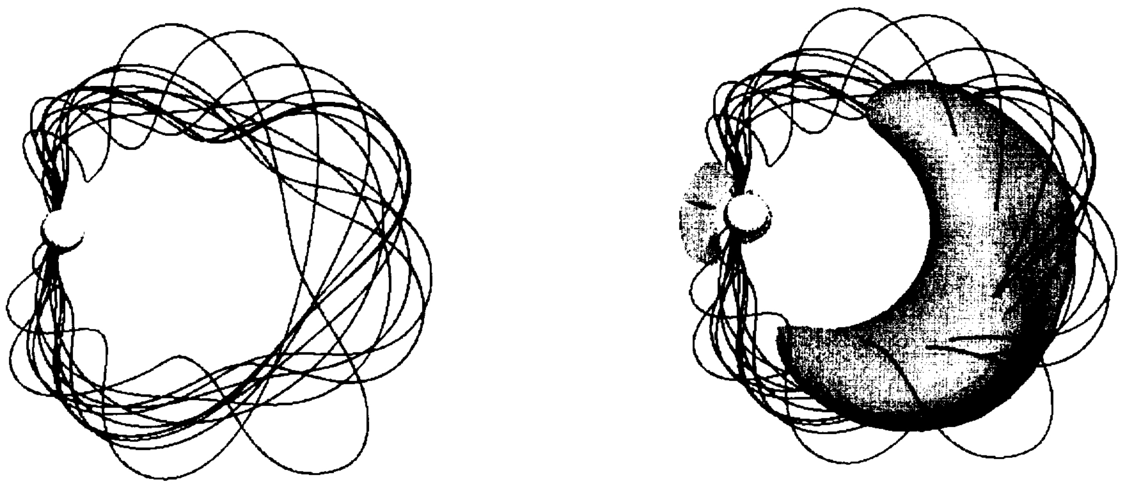




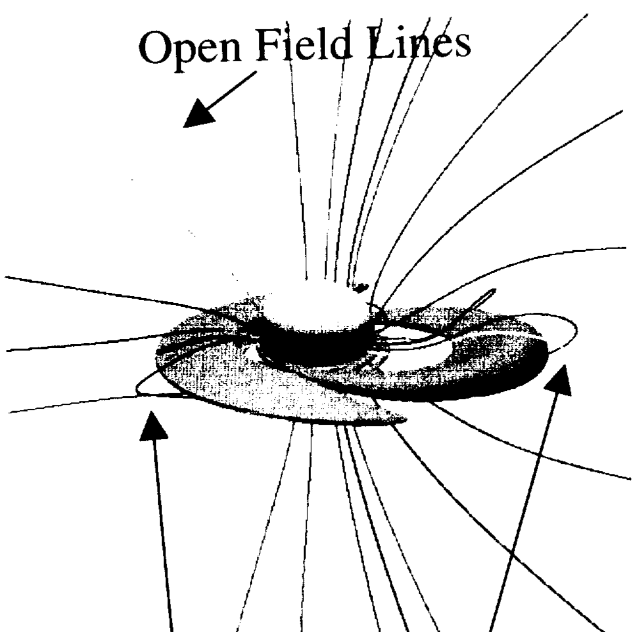
FORCE-FREE FITTING OF SIMULATED CME EJECTA

- Simulated ejecta is highly idealized, but nevertheless can yield useful insights into strengths and limitations of simple force-free fits
- Variations in force free parameter α were not too large, but α shows some non uniformity in evolution
- Force-free model fits the flux rope quite well (not surprising for 2-D: flux rope axis is known).
- Interior of flux rope is force-free, even at 1 A.U.
- Weakness of the force-free fit appears to be in the assumed shape of the flux rope
- More realistic simulations (3D, two-state wind, rotation, etc.) are required and are currently in progress.

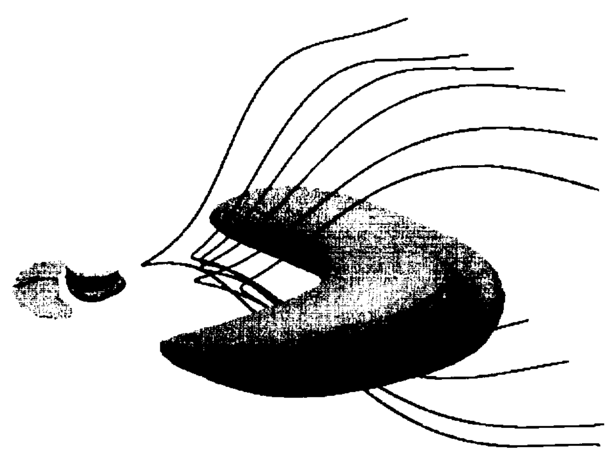
3D CME Eruption: Magnetic Field Topology



Flux Rope Connected to the Sun



Closed or Overylying Field Lines



Disconnected or
U–shaped Field Lines

THE FUTURE

- Simulation of CME propagation to 1 A.U. (and beyond) is entering a stage where real progress can be made.
- Not a moment too soon! We have many puzzles, and important upcoming observational opportunities (e.g., STEREO).
- The only way we will resolve which physical mechanism initiates CMEs will be to refine the models until they can *directly* address observations
- For example, we should try to track the evolution of an active region with detailed vector magnetograms, while comparing model output to observed quantities (*e.g.*, X-ray emission, EUV emission). This requires significant improvements to present models.
- In situ measurements provide the ultimate test of the CME evolution predicted by the models.
- The models may in turn help us gain more insight into the interplanetary data, and devise improved analysis methods.

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In this report we describe progress in our investigation of CMEs using magnetohydrodynamic (MHD) simulations.

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