PROGRESS AND CHALLENGES IN MODELING THE MAY 12, 1997 CME

ZORAN MIKIĆ
JON A. LINKER
ROBERTO LIONELLO
PETE RILEY

SCIENCE APPLICATIONS INTL. CORP.
SAN DIEGO

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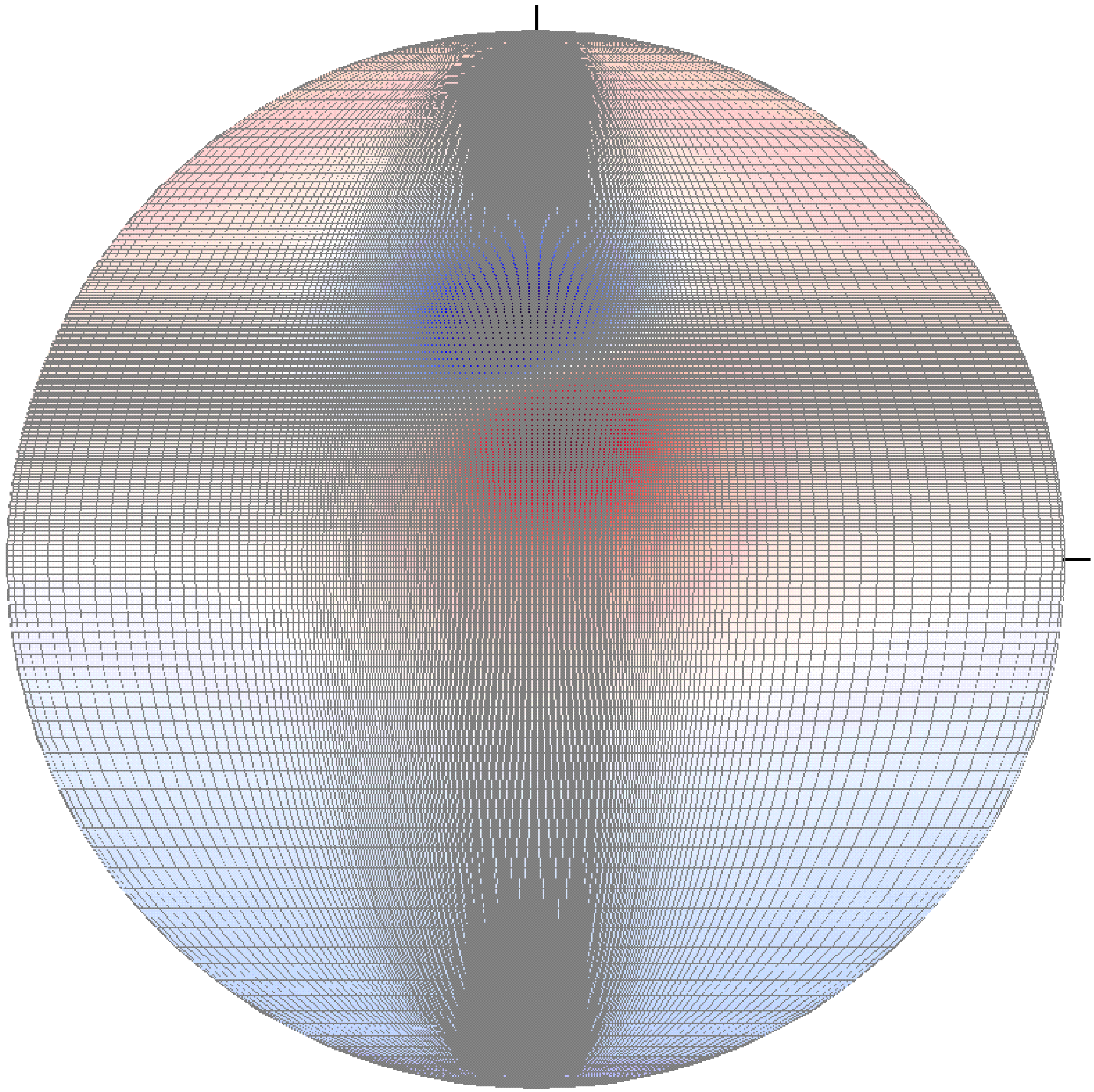
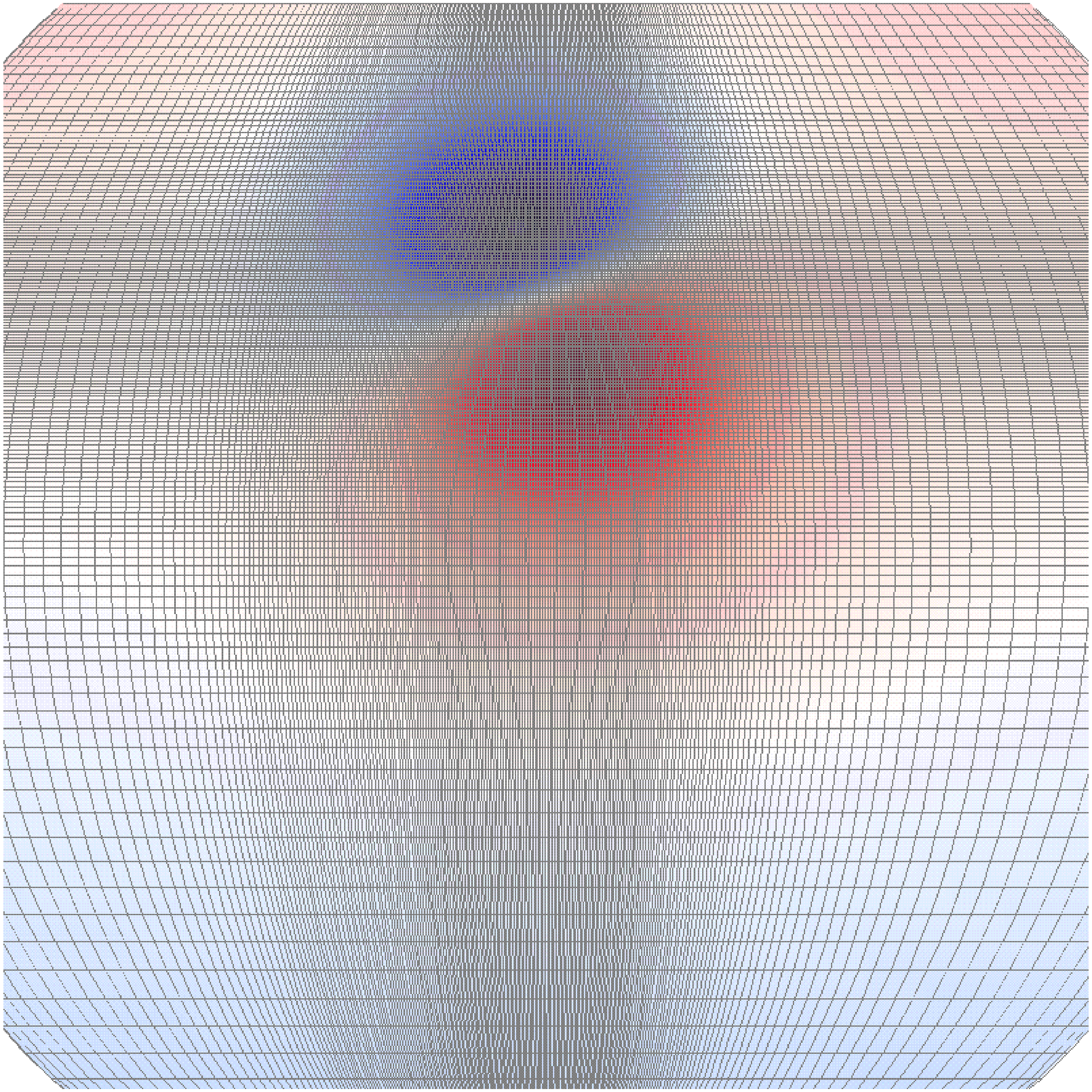
Steps Needed to Model the May 12, 1997 Event

- Initial equilibrium:
  - Large localized *B* in the active region
  - Nonuniform meshes are essential
  - Helmet streamer with solar wind
  - Nonuniform density and pressure at the lower coronal boundary
  - Energized (twisted, sheared) field $\Rightarrow$ vector magnetograms
- Eruption mechanism (*e.g.*, flux cancellation, breakout)
- Ability to simulate the CME
  - Even higher spatial resolution
  - Large flows and electric currents
- Track the propagation of the CME in interplanetary space

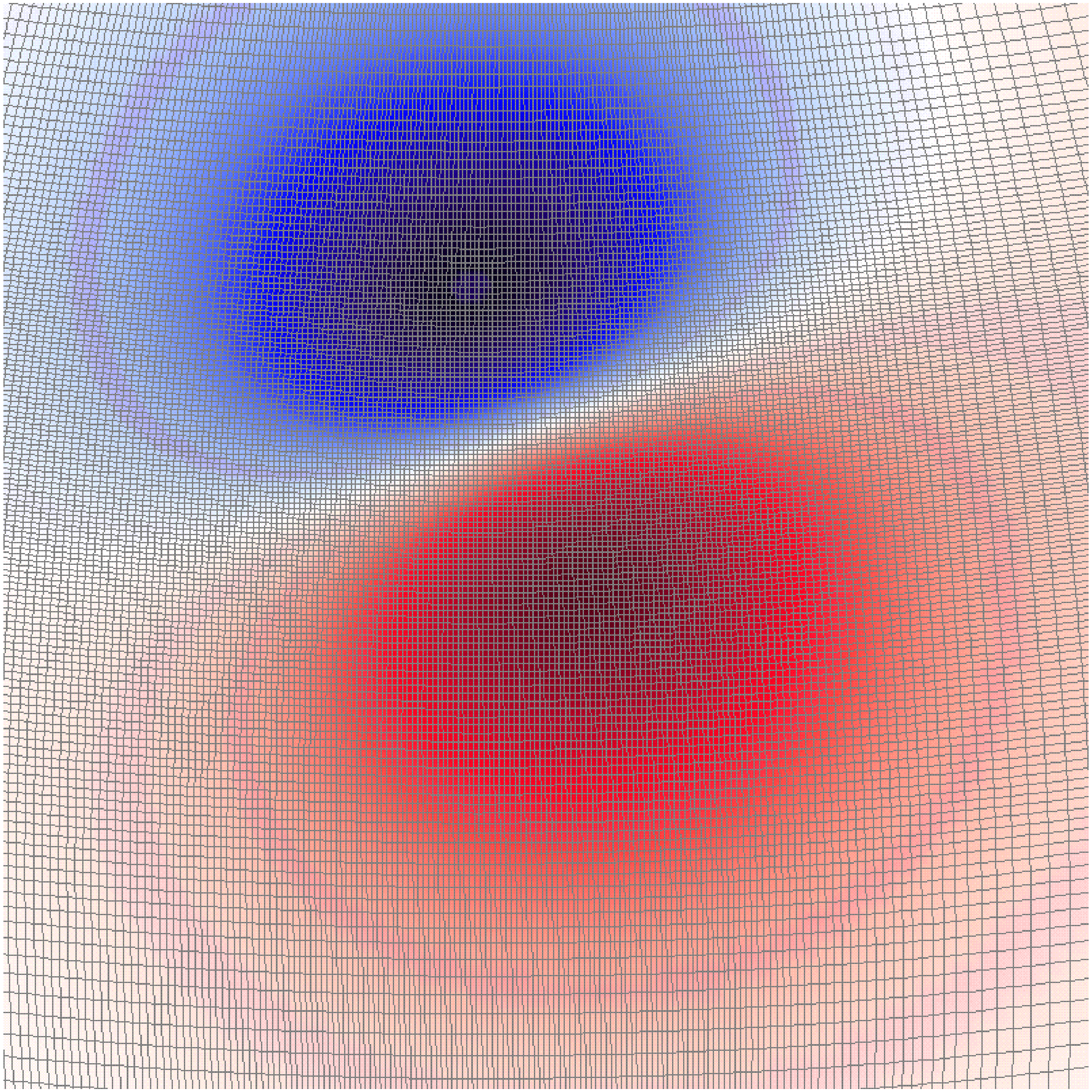
Nonuniform Mesh



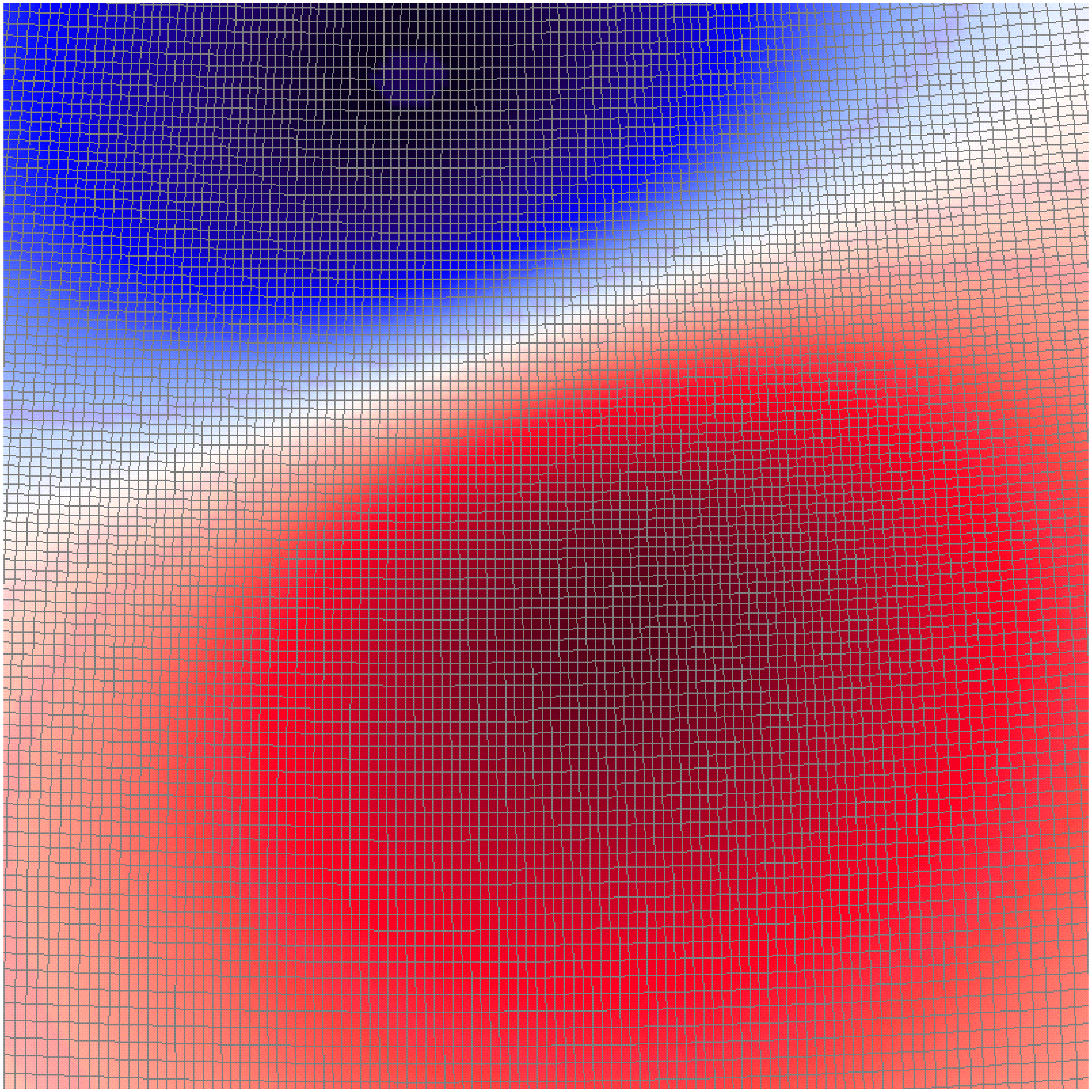
Nonuniform Mesh



Nonuniform Mesh



Nonuniform Mesh



MHD Equations
(Polytropic Model)

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

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

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

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

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

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

$\gamma = 1.05$ in the corona

INITIAL STATE

- We have performed a progression of cases with decreasing size of the active region and increasing B
- The density needs to be higher in the active region to have "reasonable" Alfvén speed

  $\Rightarrow$ nonuniform density and pressure at the lower coronal boundary
- How do we initialize the pressure and density in the domain?
- Nonuniform meshes ranging from 91 × 81 × 81 to 161 × 161 × 161 (r,θ,ϕ) mesh points

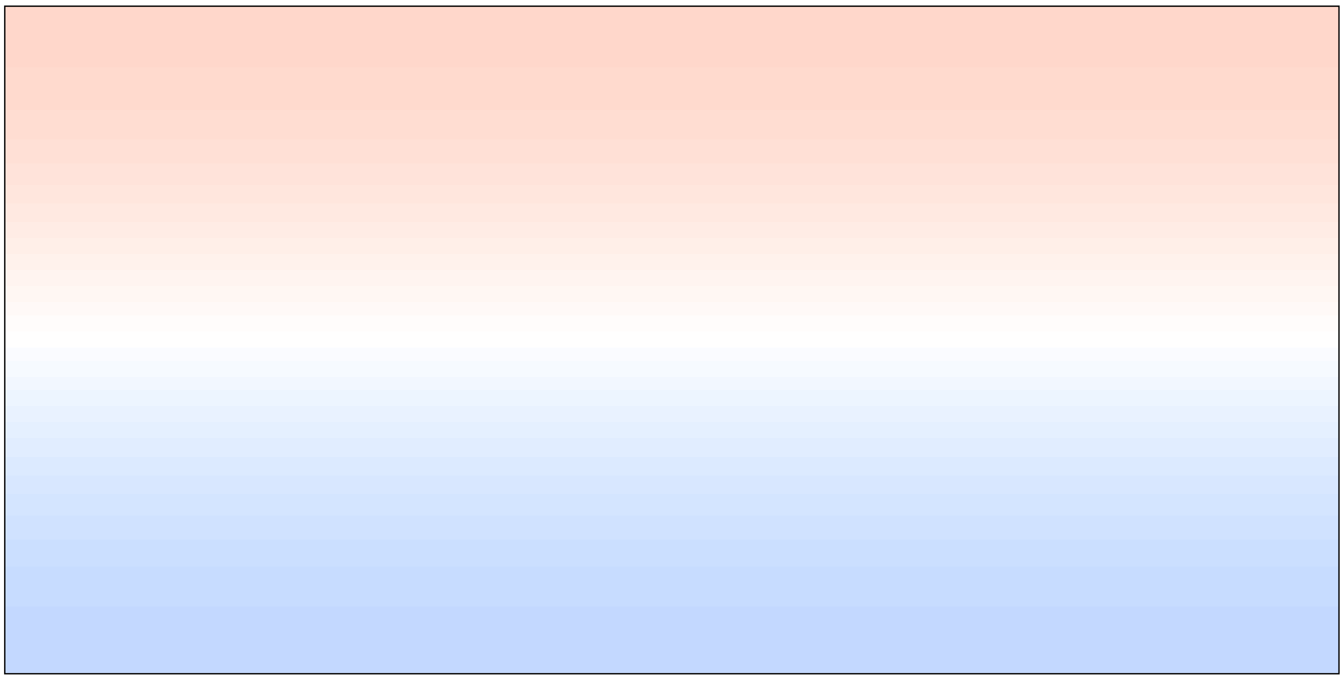
  $\Delta r_{max}/\Delta r_{min} \sim 600$, $\Delta\theta_{max}/\Delta\theta_{min} \sim 10$, $\Delta\phi_{max}/\Delta\phi_{min} \sim 20$

  $\Delta r_{min} \sim .003 R_S$ (2000 km), $\Delta\theta_{min} \sim \Delta\phi_{min} \sim 0.3°$
- The run took ~ 18 hours on 512 processors of an IBM/SP4 during the initial relaxation phase

CASE 1

- Axisymmetric dipole field
- $B \sim 3.3$ G (at the pole) → $B \sim 1.65$ G (equator)
- $n_o \sim 2 \times 10^8$ cm^{-3} (uniform)
- $v_A \sim 485$ km/s (pole) → 242 km/s (equator)

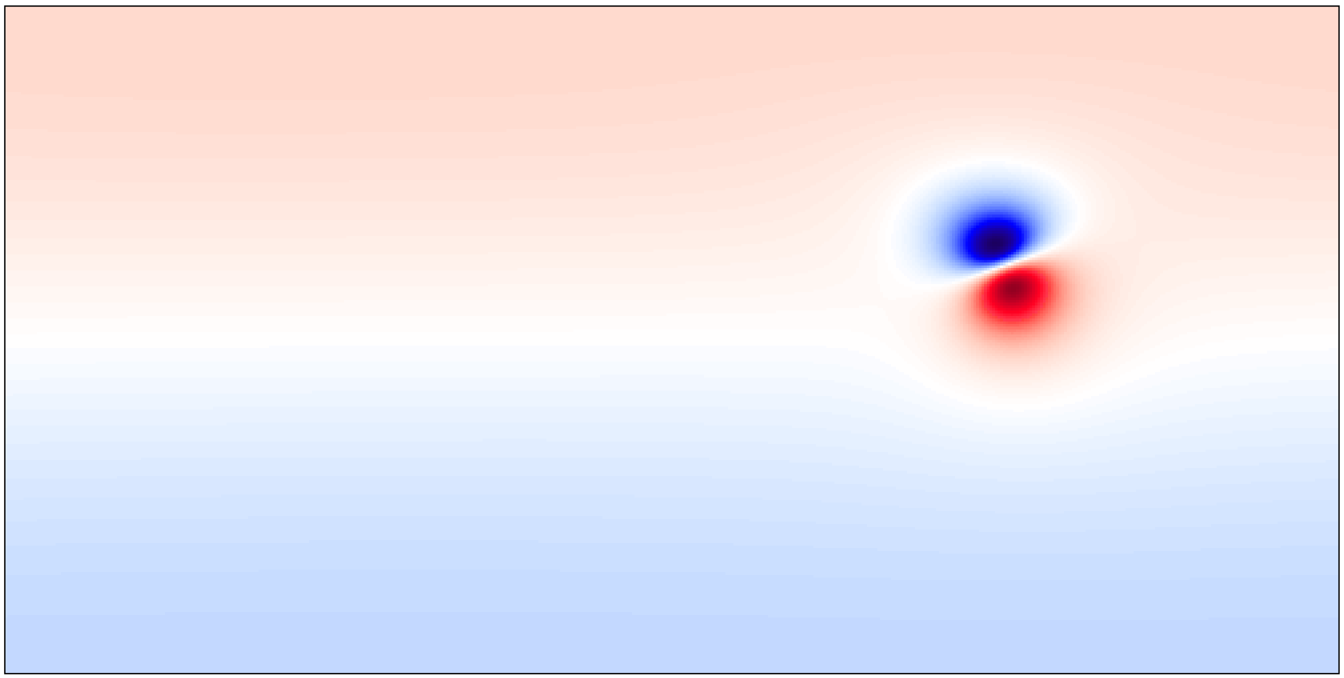
B_r at $r = R_o$



Case 2

- Dipole field + bipole (relatively large scale)
- $B \sim 3.3$ G (at the pole) $\rightarrow B \sim 28$ G (active region)
- $n_o \sim 2 \times 10^8$ cm^{-3} (pole) $\rightarrow 5 \times 10^8$ cm^{-3} (active region)
- $v_A \sim 485$ km/s (pole) $\rightarrow$ 2700 km/s (active region)

B_r at $r = R_o$



CASE 3

- Dipole field + bipole (intermediate scale)
- $B \sim 3.3$ G (at the pole) → $B \sim 220$ G (active region)
- $n_o \sim 2 \times 10^8$ cm^{-3} (pole) → 4×10^9 cm^{-3} (active region)
- $v_A \sim 485$ km/s (pole) → 7500 km/s (active region)

B_r at $r = R_o$

CASE 4

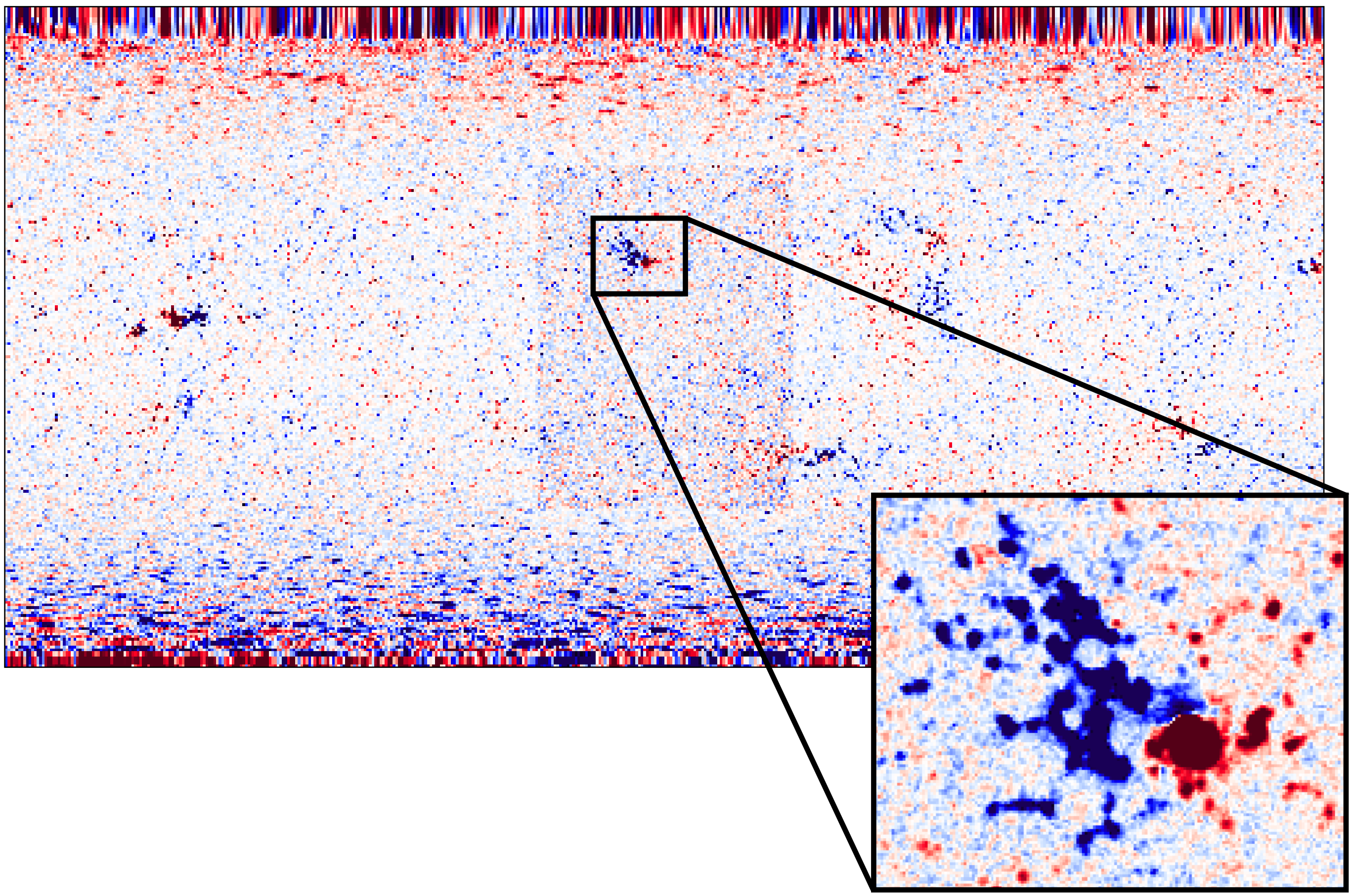
- Dipole field + bipole (small scale)
- $B \sim 9$ G (at the pole) $\rightarrow$ $B \sim 1000$ G (active region)
- $n_o \sim 2 \times 10^8$ cm^{-3} (pole) $\rightarrow$ 8×10^{10} cm^{-3} (active region)
- $v_A \sim 1350$ km/s (pole) $\rightarrow$ 7700 km/s (active region)

B_r at $r = R_o$

CASE 5

- MDI magnetogram on May 11, 1997 (courtesy of Phil Scherrer and Yang Liu)
- B ~ ??? G (N pole), ??? G (S pole)
- B ~ 2000 G (active region) [raw]

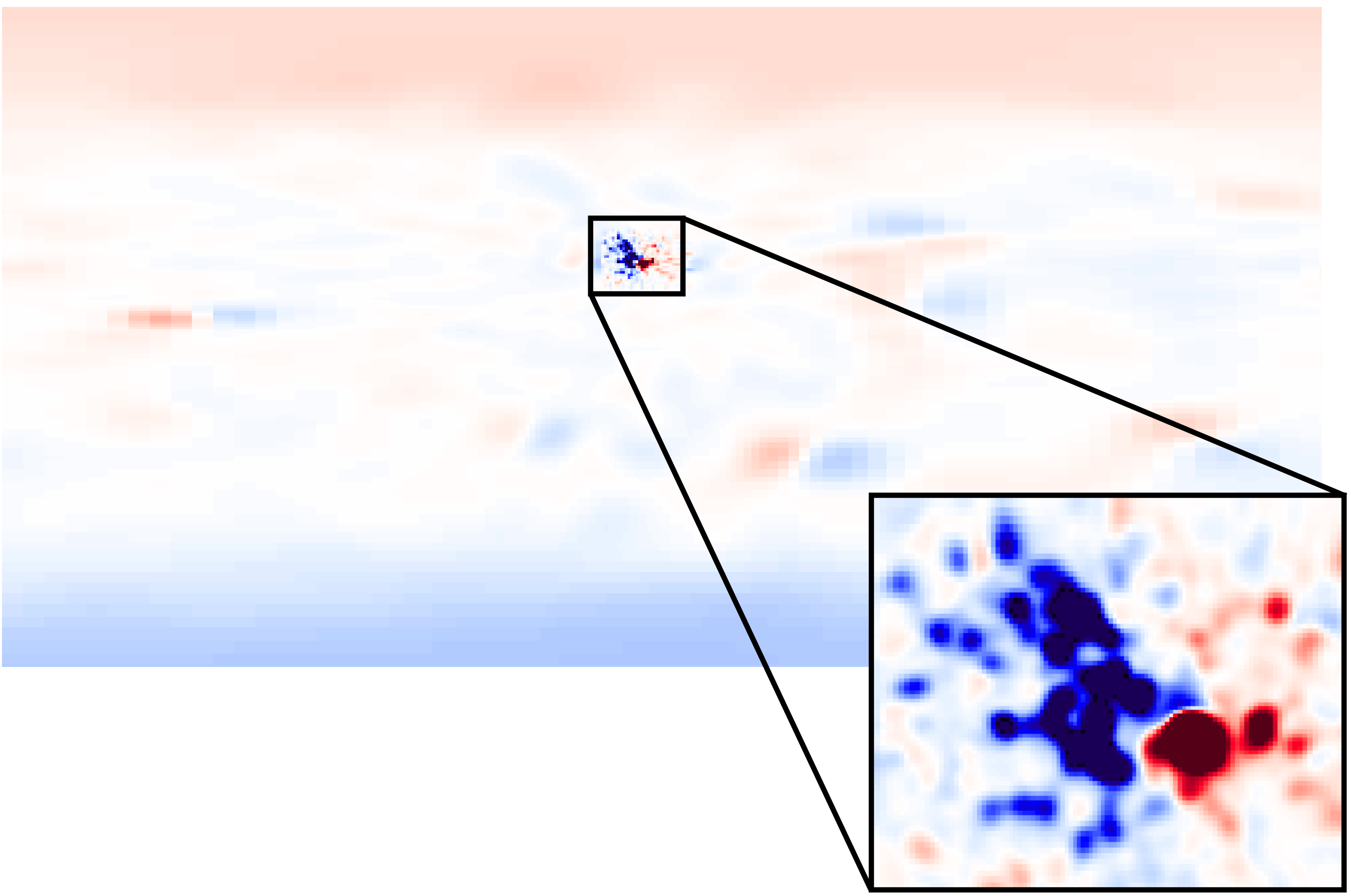
B_r at $r = R_o$



CASE 5

- MDI magnetogram on May 11, 1997 (courtesy of Phil Scherrer and Yang Liu)
- $B \sim 20$ G (N pole), 30 G (S pole)
- $B \sim 1000$ G (active region) [filtered]

B_r at $r = R_o$



GUIDANCE FROM MHD MODELS OF ACTIVE REGIONS

- We have developed sophisticated models of temperature and density distributions in active regions for prescribed coronal heating profiles (e.g., heating $\propto$ *B)*
- We can use these to characterize the Alfvén speed profile in active regions
- In this model the density at the base of the corona (and in the transition region) is determined by a balance between thermal conduction in the corona and radiation loss in the transition region (Rosner *et al.* 1978; Withbroe 1988):

$$\nabla\cdot(\kappa_{\|}\hat{\mathbf{b}}\hat{\mathbf{b}}\cdot\nabla T) \sim n_e n_p Q(T)$$

- We can then choose the appropriate density in the polytropic model to give an appropriate Alfvén speed:

e.g., $\rho_0(\theta,\phi) \sim B$

- Ultimately, this can be done self-consistently with a full treatment including the improved energy equation

MHD EQUATIONS
(IMPROVED ENERGY EQUATION MODEL)

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

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

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

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

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

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

$$\gamma = 5/3$$

$$\mathbf{q} = -\kappa_{\parallel}\hat{\mathbf{b}}\hat{\mathbf{b}}\cdot\nabla T$$ (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

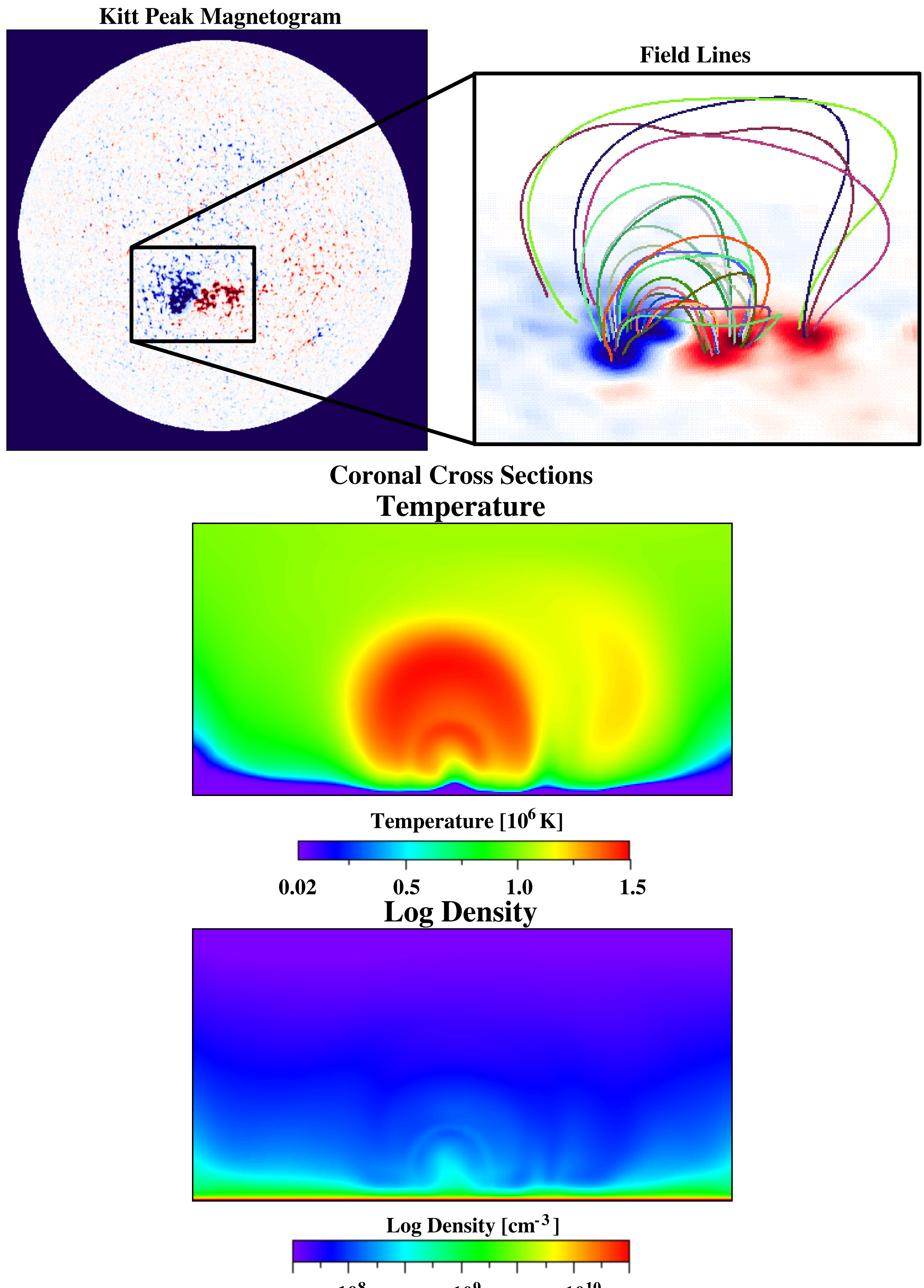
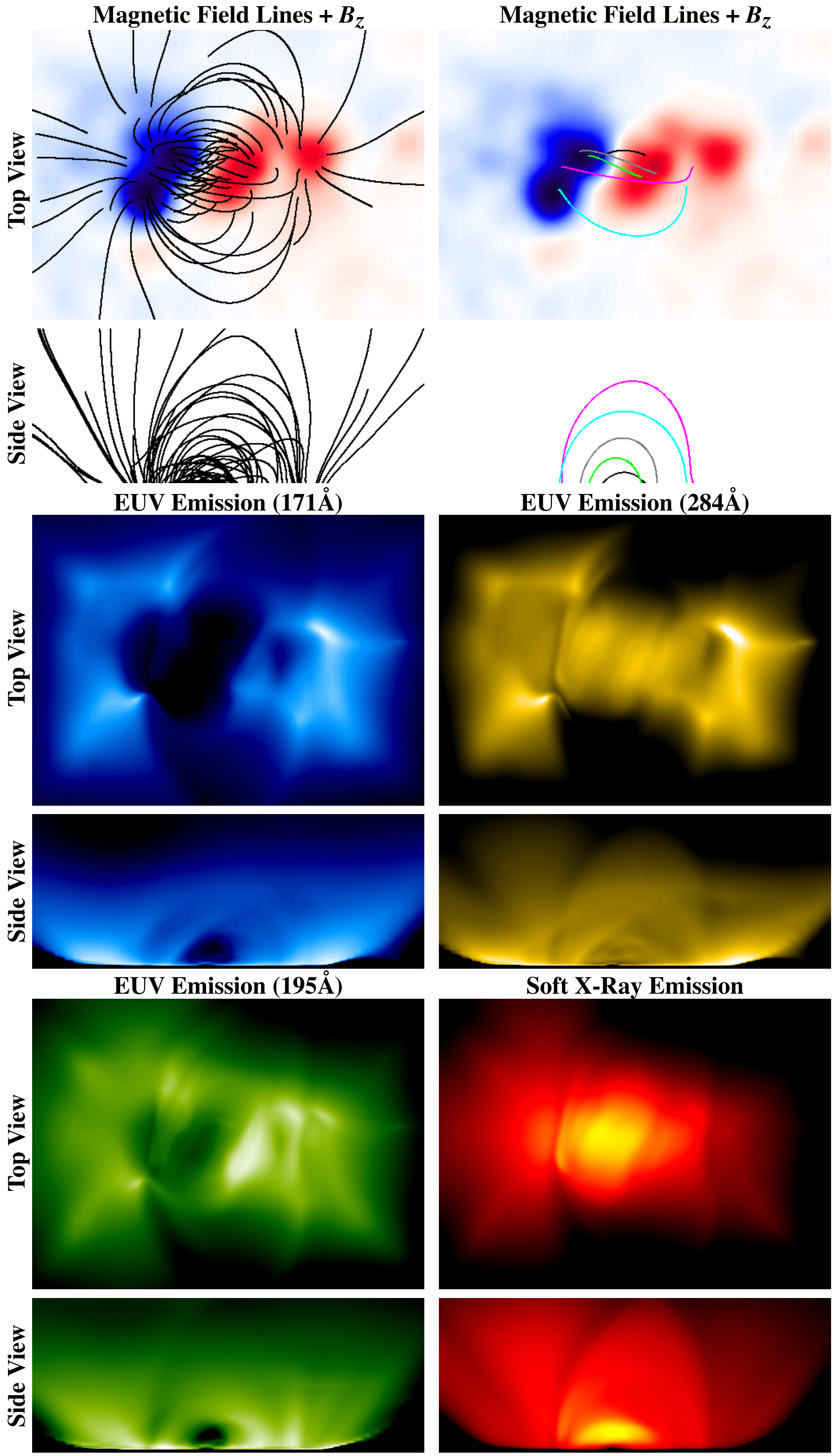
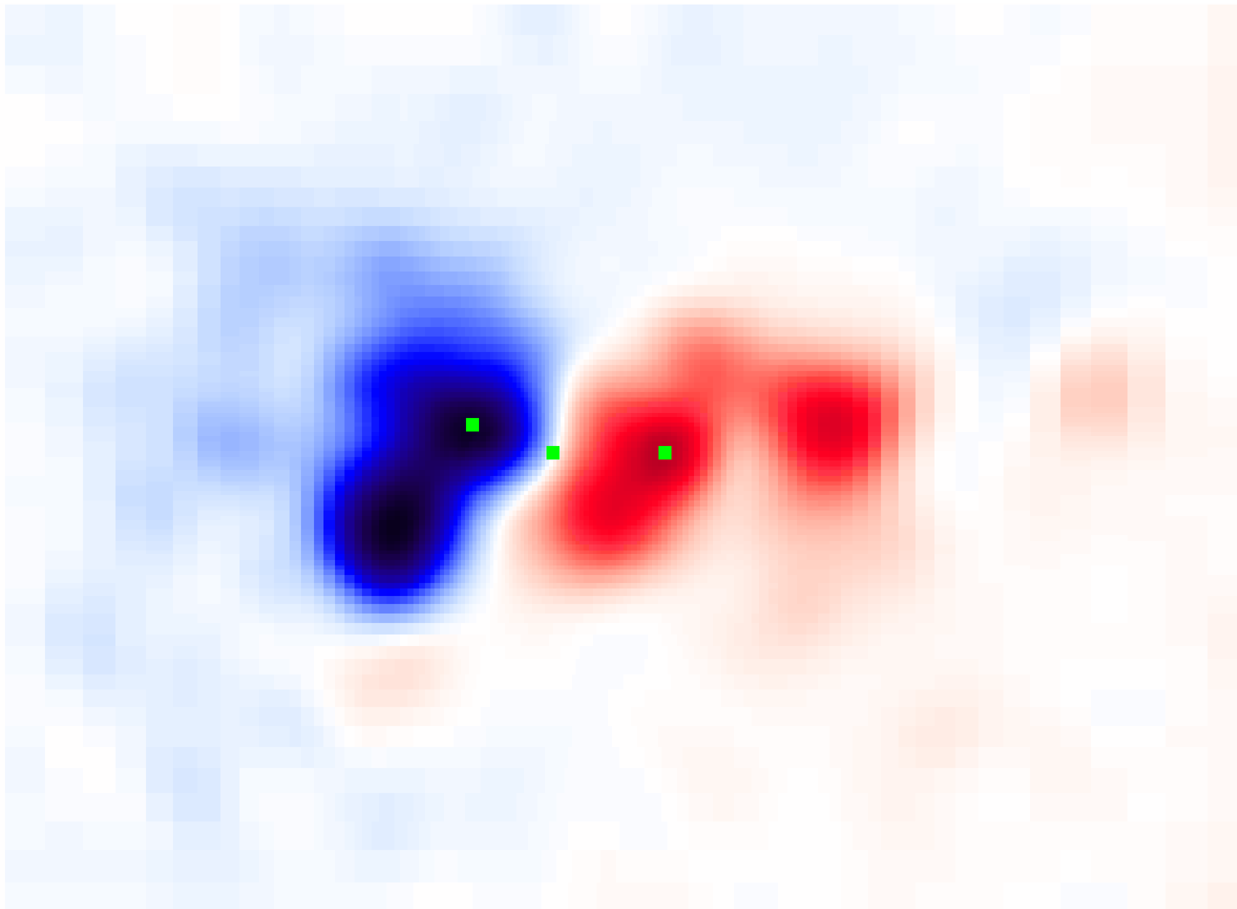
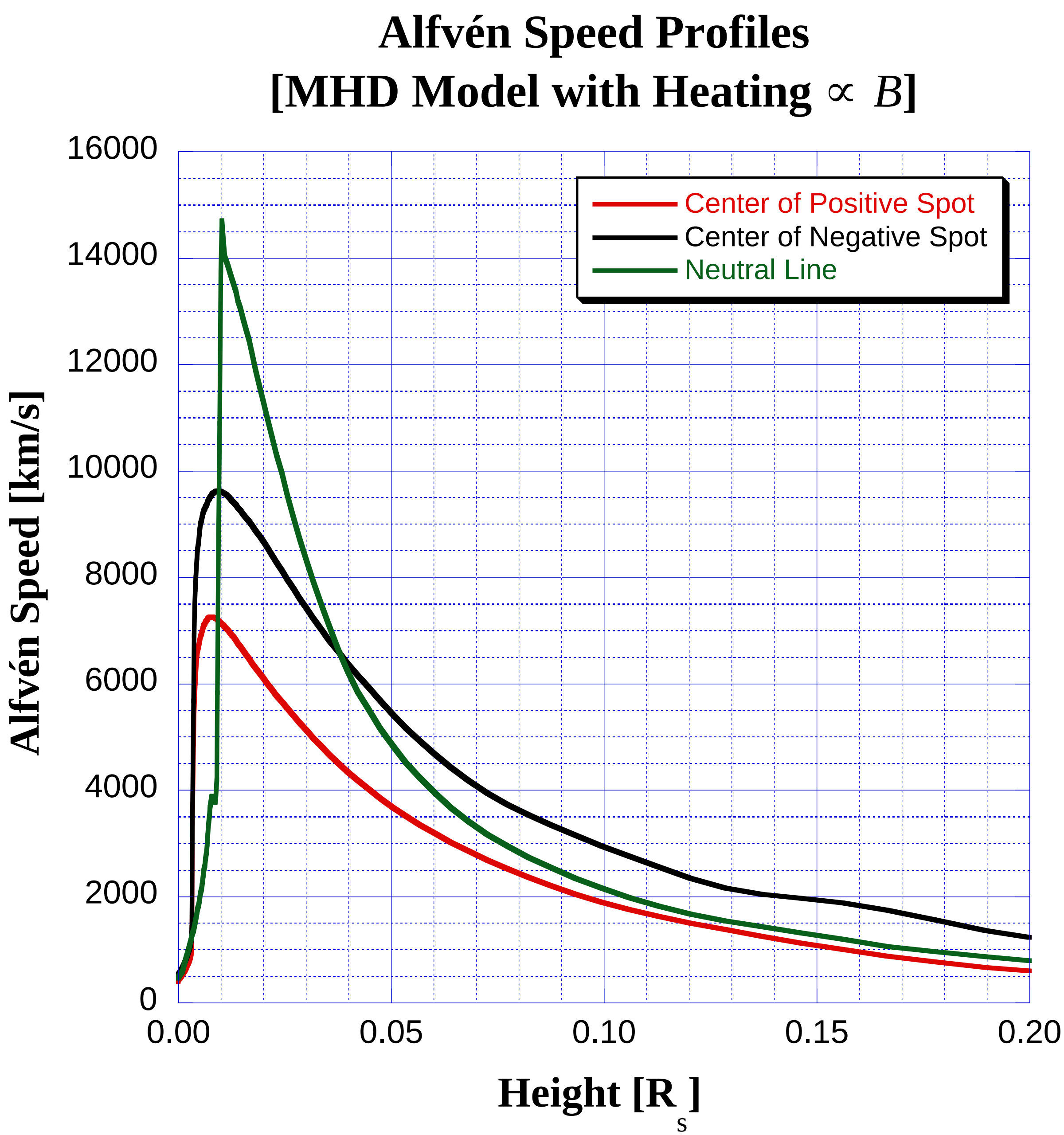


Figure 1. Modeling the magnetic and thermal structure of an active region on August 29, 1996. A Kitt Peak magnetogram is used to specify the normal component of the magnetic field. A twist is applied to the field, and the steady state is calculated for a given coronal heating distribution. The temperate and density structure shows that the transition region height varies in different parts of the active region.


Magnetic Field Lines + B_z
Magnetic Field Lines + B_z
Top View
Side View
EUV Emission (171Å)
EUV Emission (284Å)
Top View
Side View
EUV Emission (195Å)
Soft X-Ray Emission
Top View
Side View

Active Region 7986, August 1996

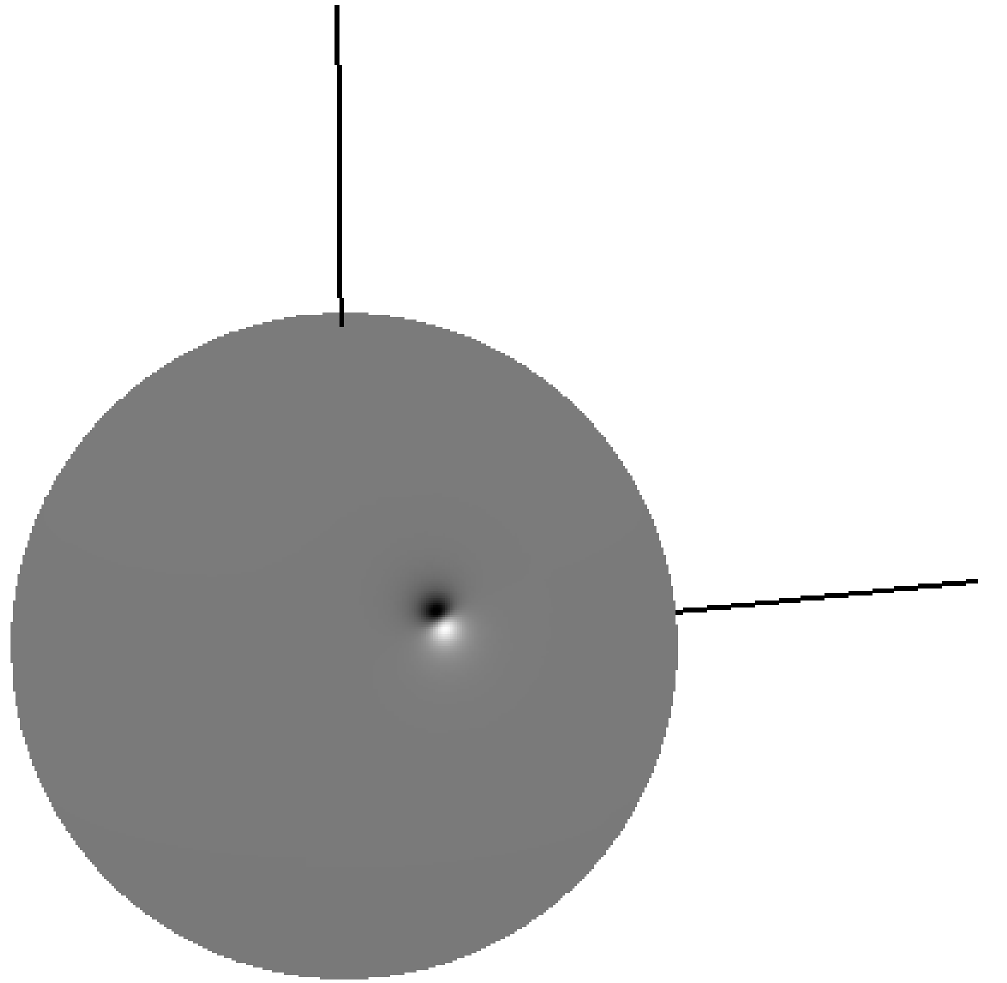



Alfvén Speed Profiles
[MHD Model with Heating ∝ B]
Alfvén Speed [km/s]
0
2000
4000
6000
8000
10000
12000
14000
16000
0.00
0.05
0.10
0.15
0.20
Height [R s]
Center of Positive Spot
Center of Negative Spot
Neutral Line

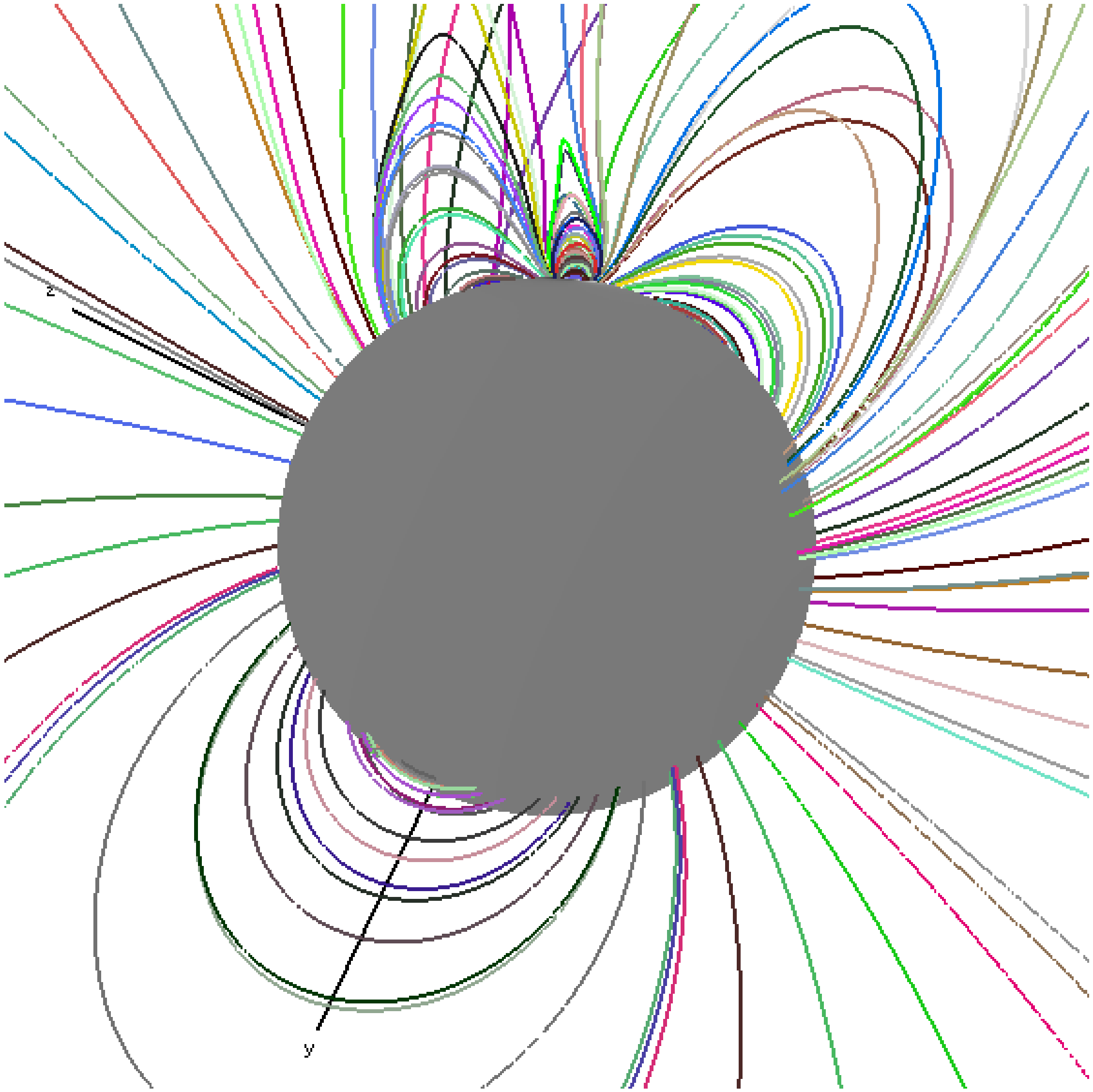
INITIAL STATE: POSSIBILITIES

- Try: hydrostatic equilibrium w.r.t. radius for the given $p_o(\theta,\phi)$ and $\rho_o(\theta,\phi)$ (not in equilibrium in θ and ϕ)
- Try: start with a cold plasma and gradually increase the boundary pressure
- Try: start with a large-scale magnetic field (B ~ 20 G), and gradually emerge a strong active region magnetic field (B ~ 1000 G) with high pressure and density

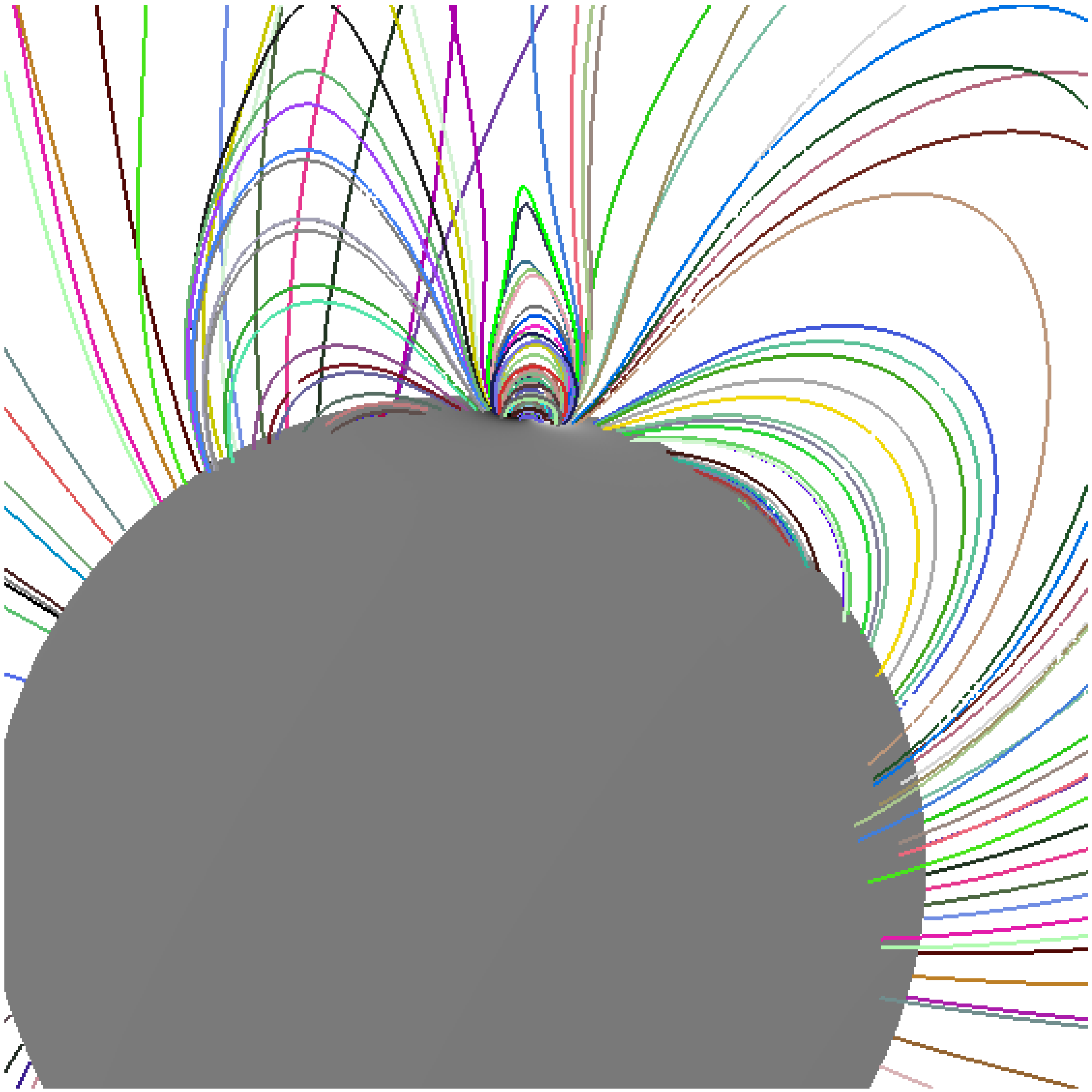
CASE 4



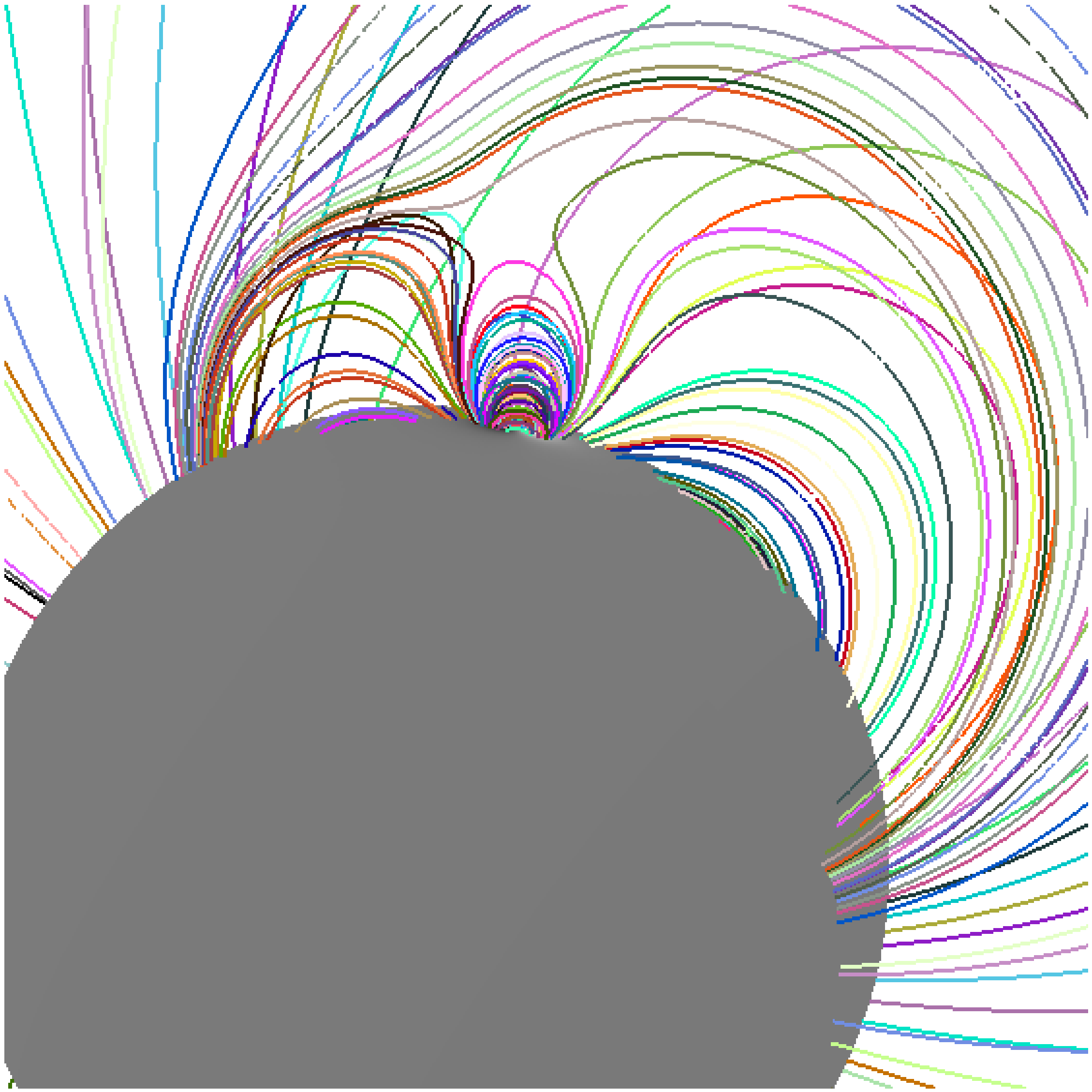
Field with Solar Wind



Field with Solar Wind

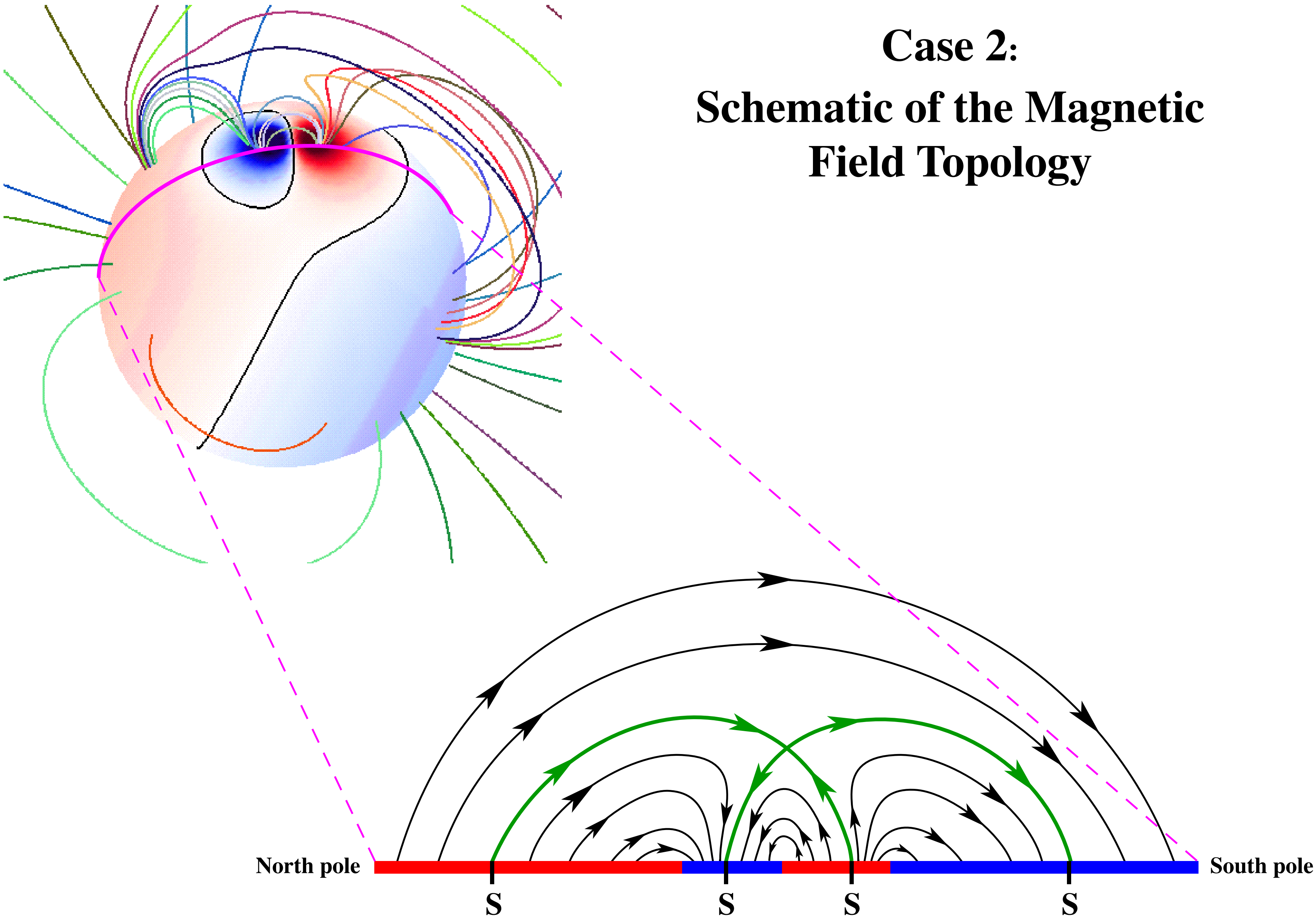


Potential Field

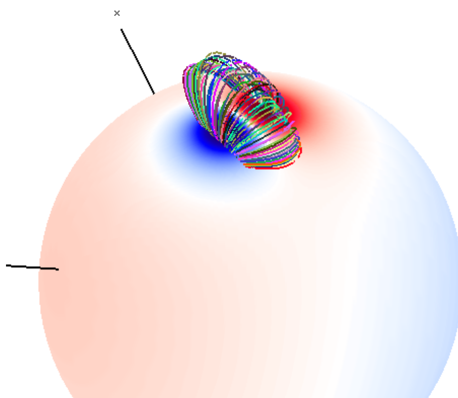


Case 2:

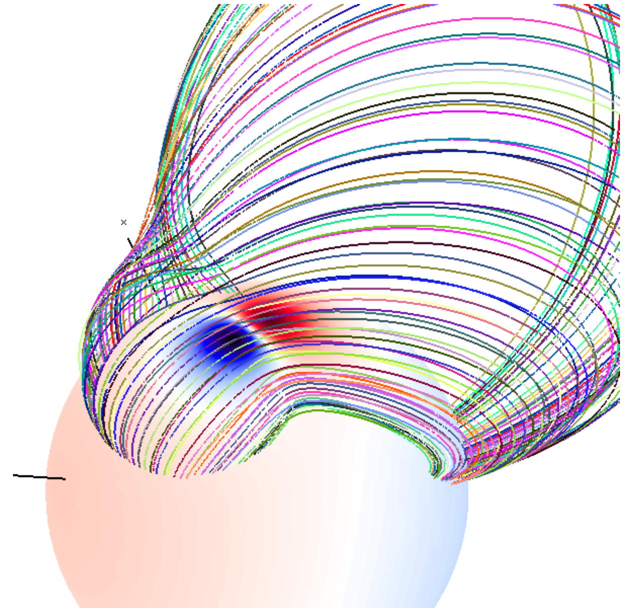
Schematic of the Magnetic Field Topology



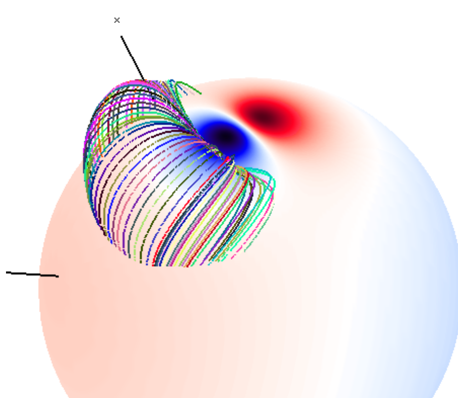
Four Flux Systems



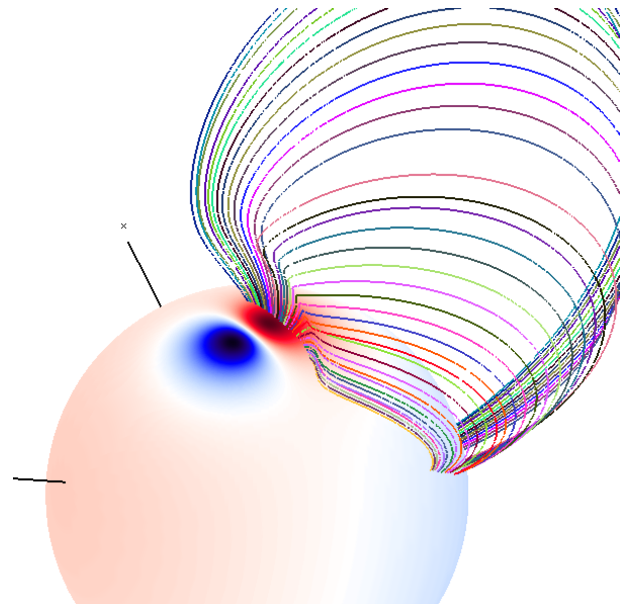
Center Arcade



Overlying Arcade

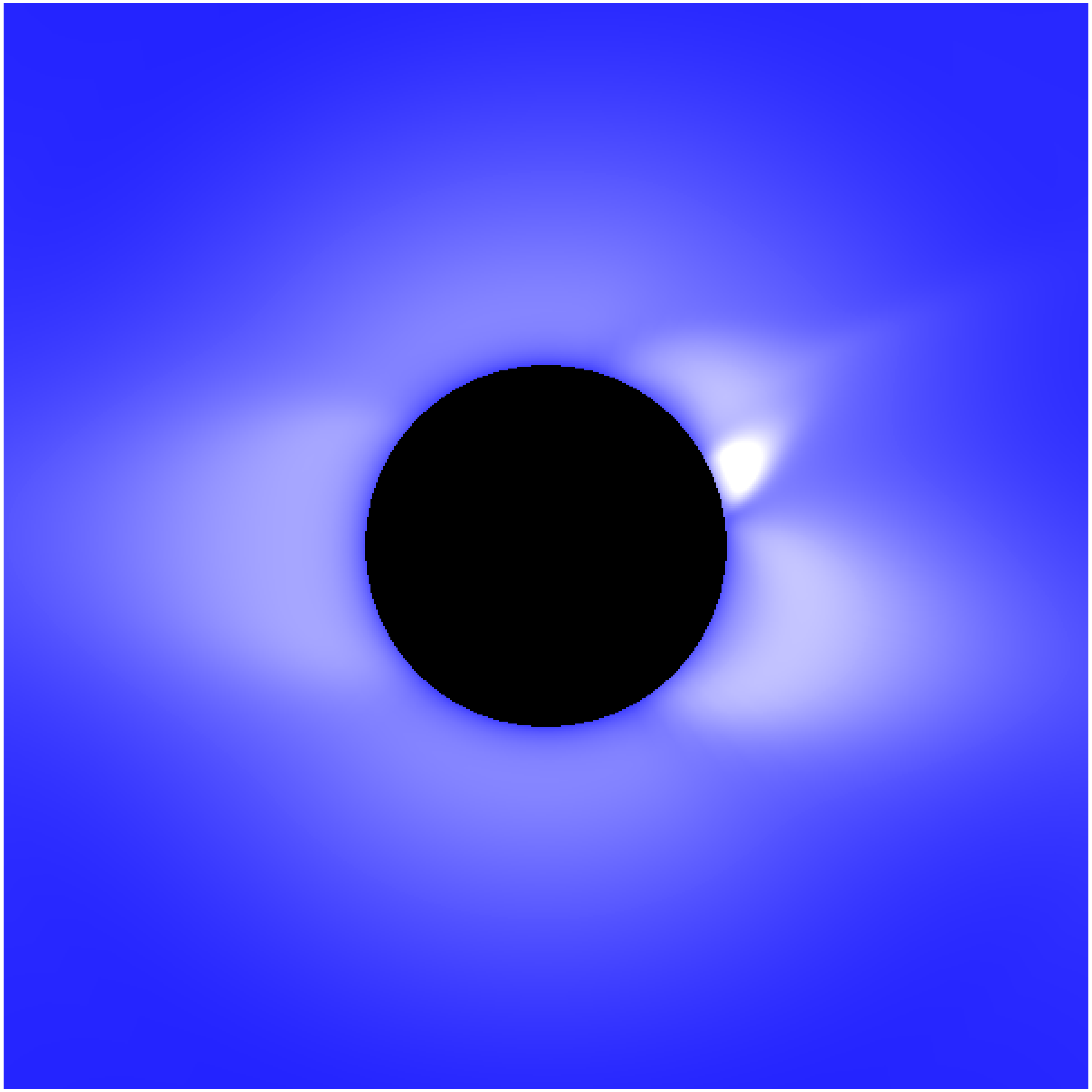


Side Arcade

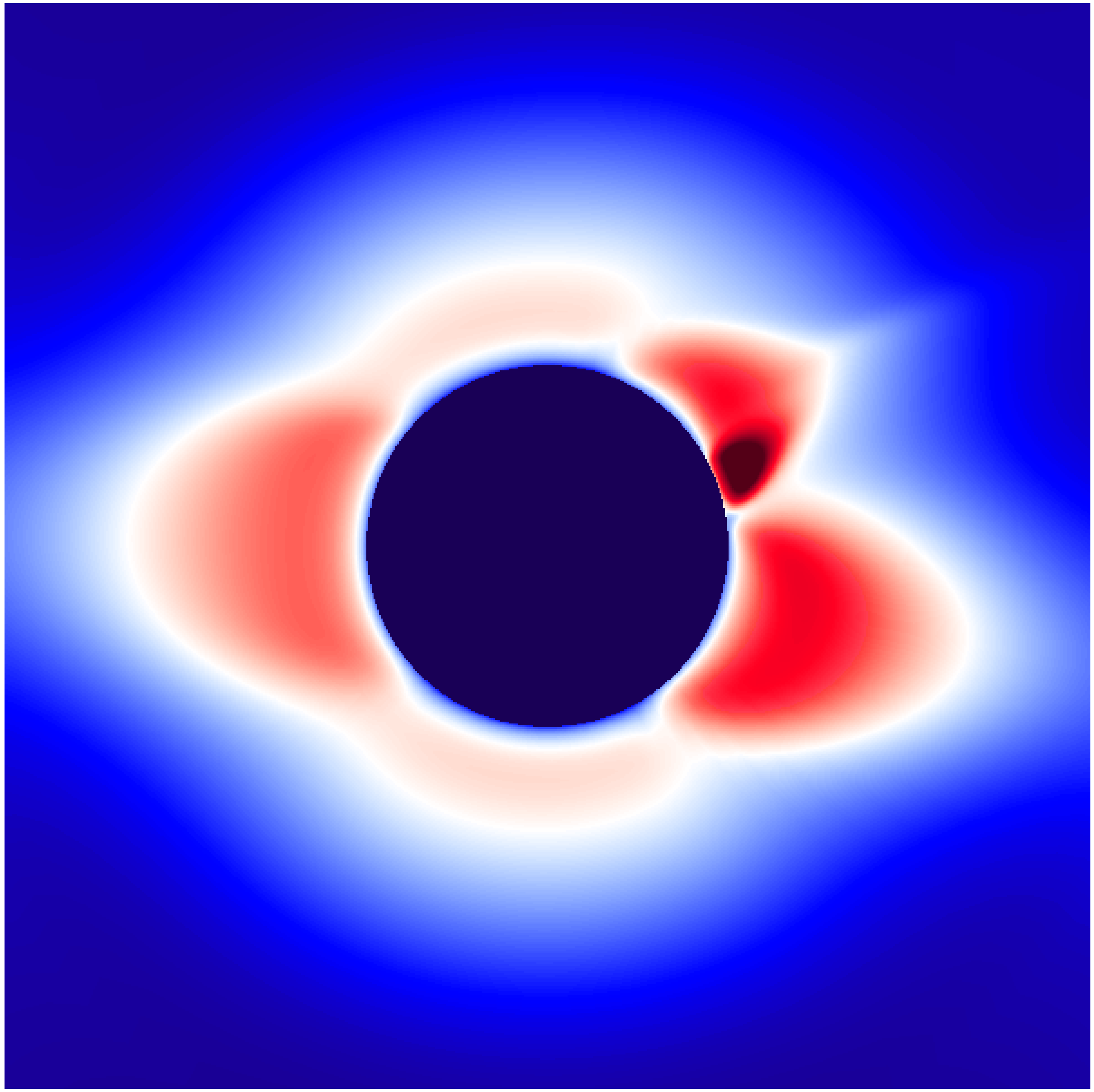


SideArcade

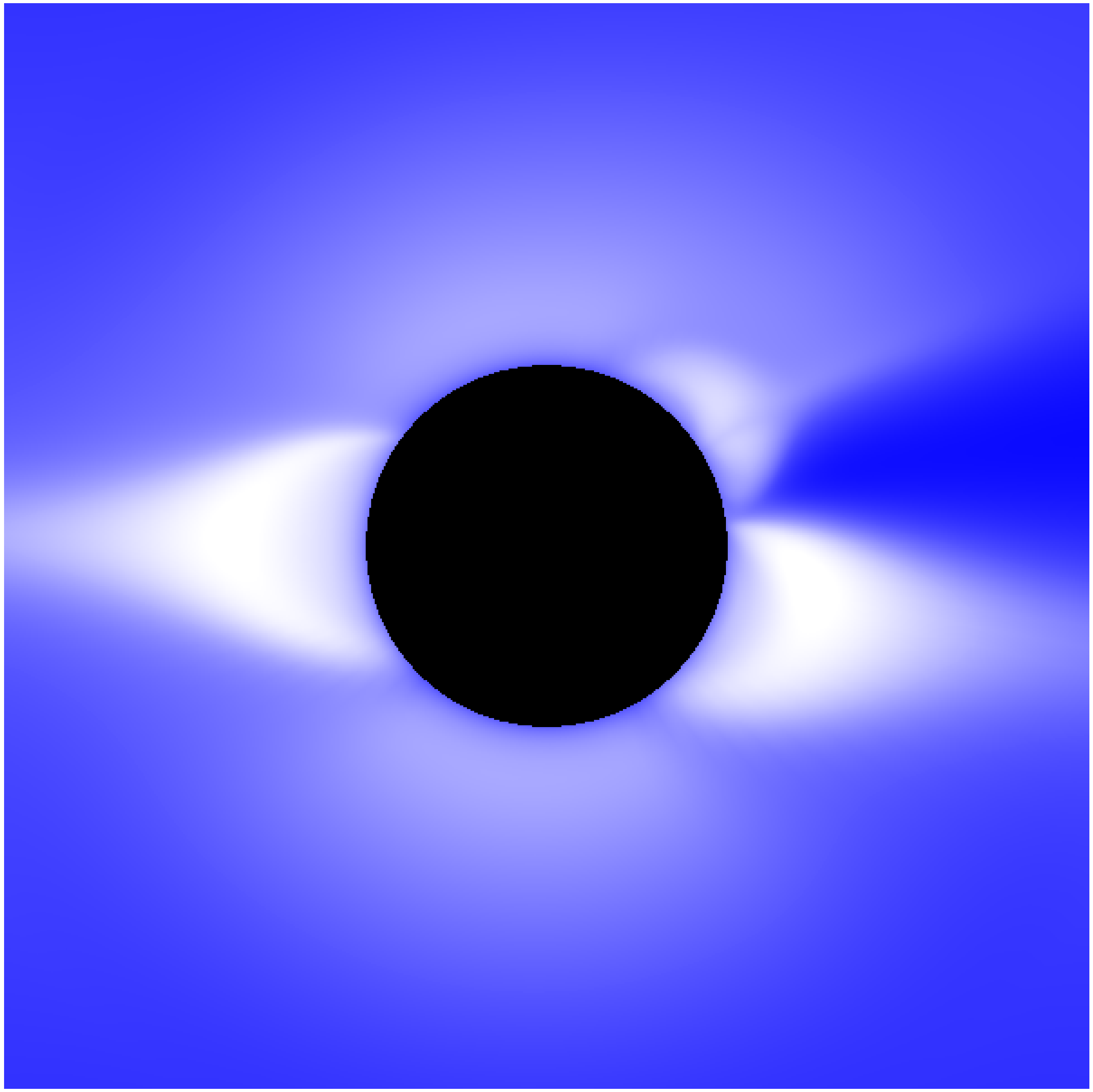
CASE 1
Polarization Brightness



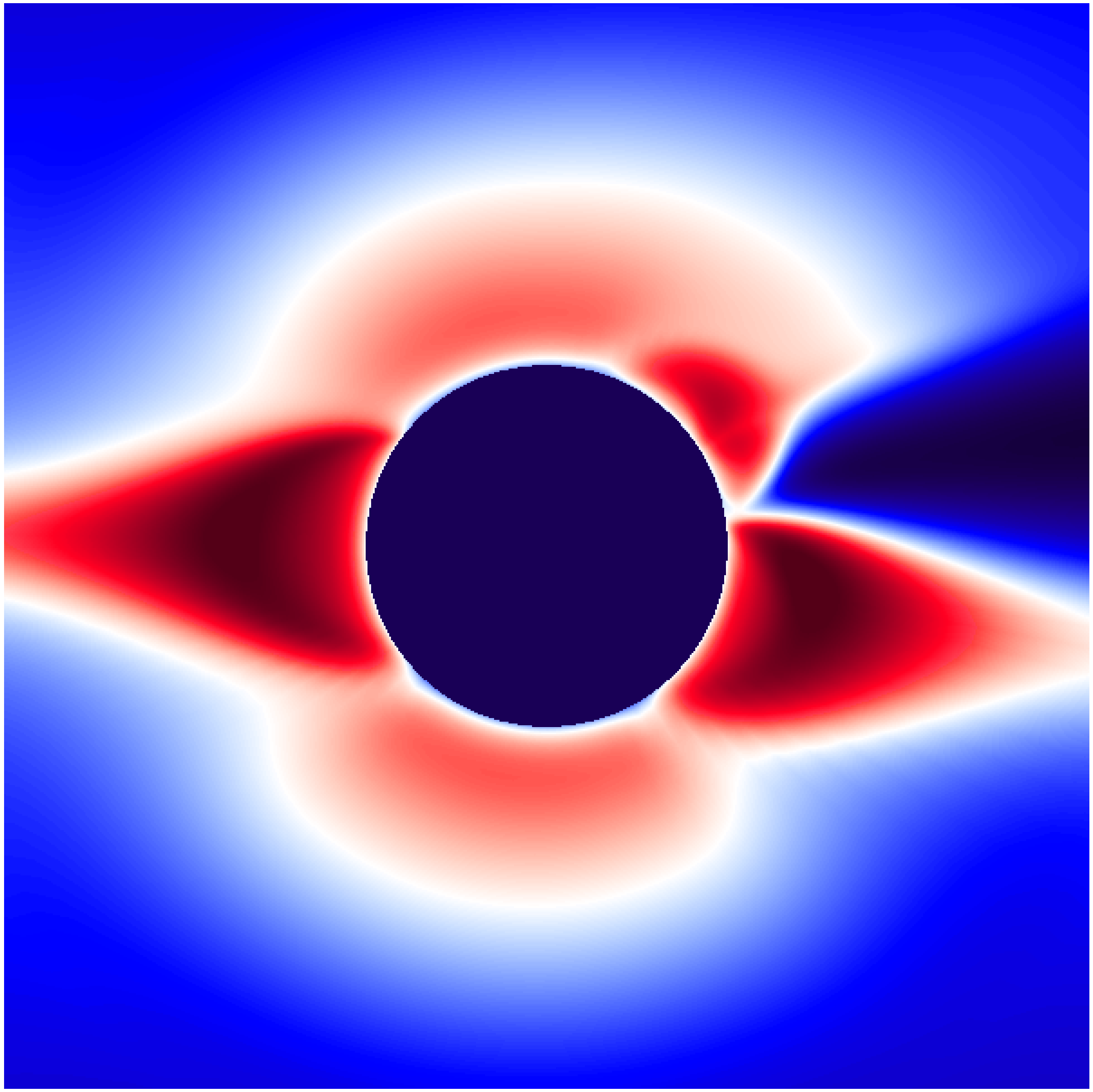
CASE 1
Polarization Brightness



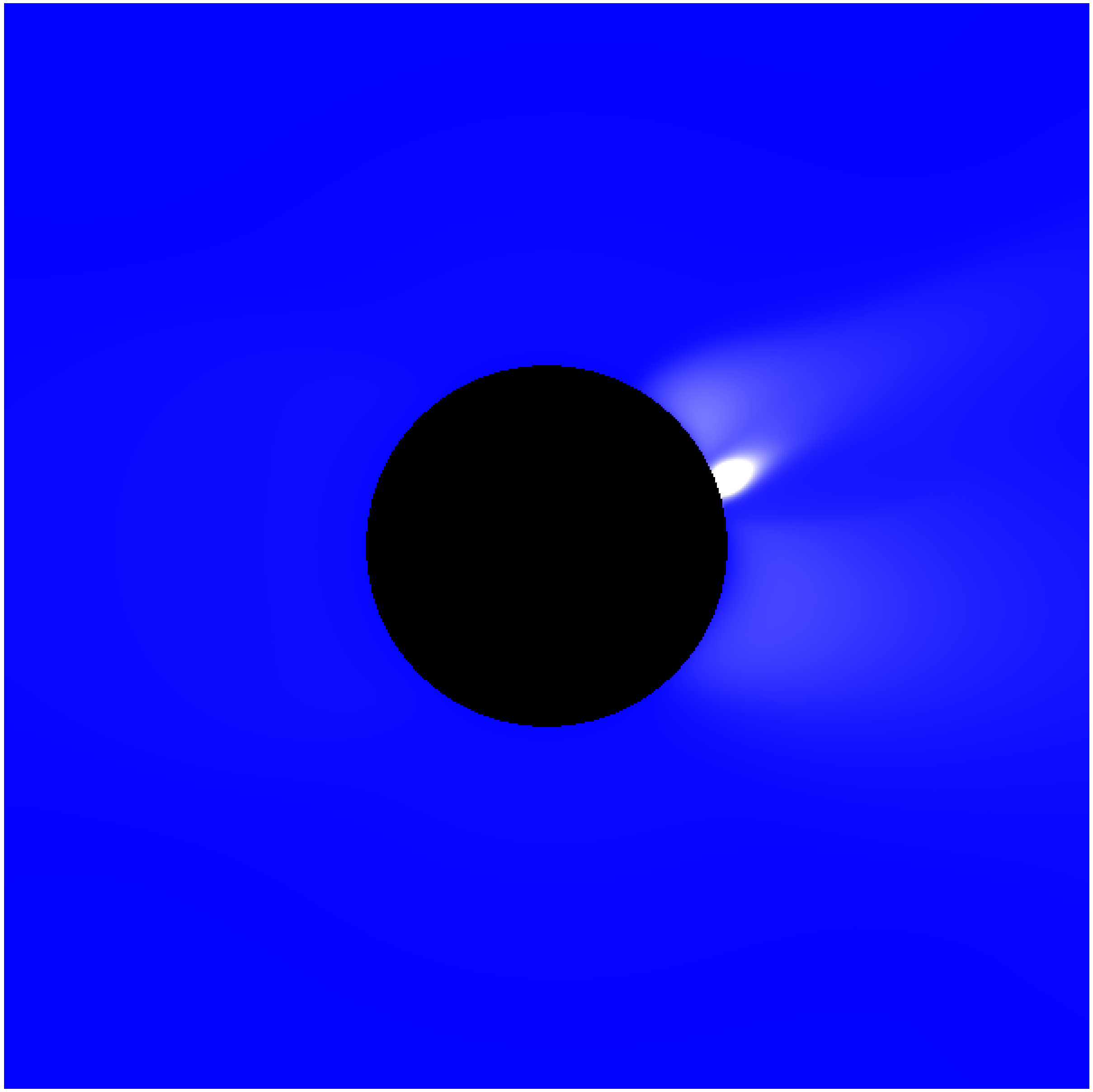
CASE 1A (uniform □o)
Polarization Brightness



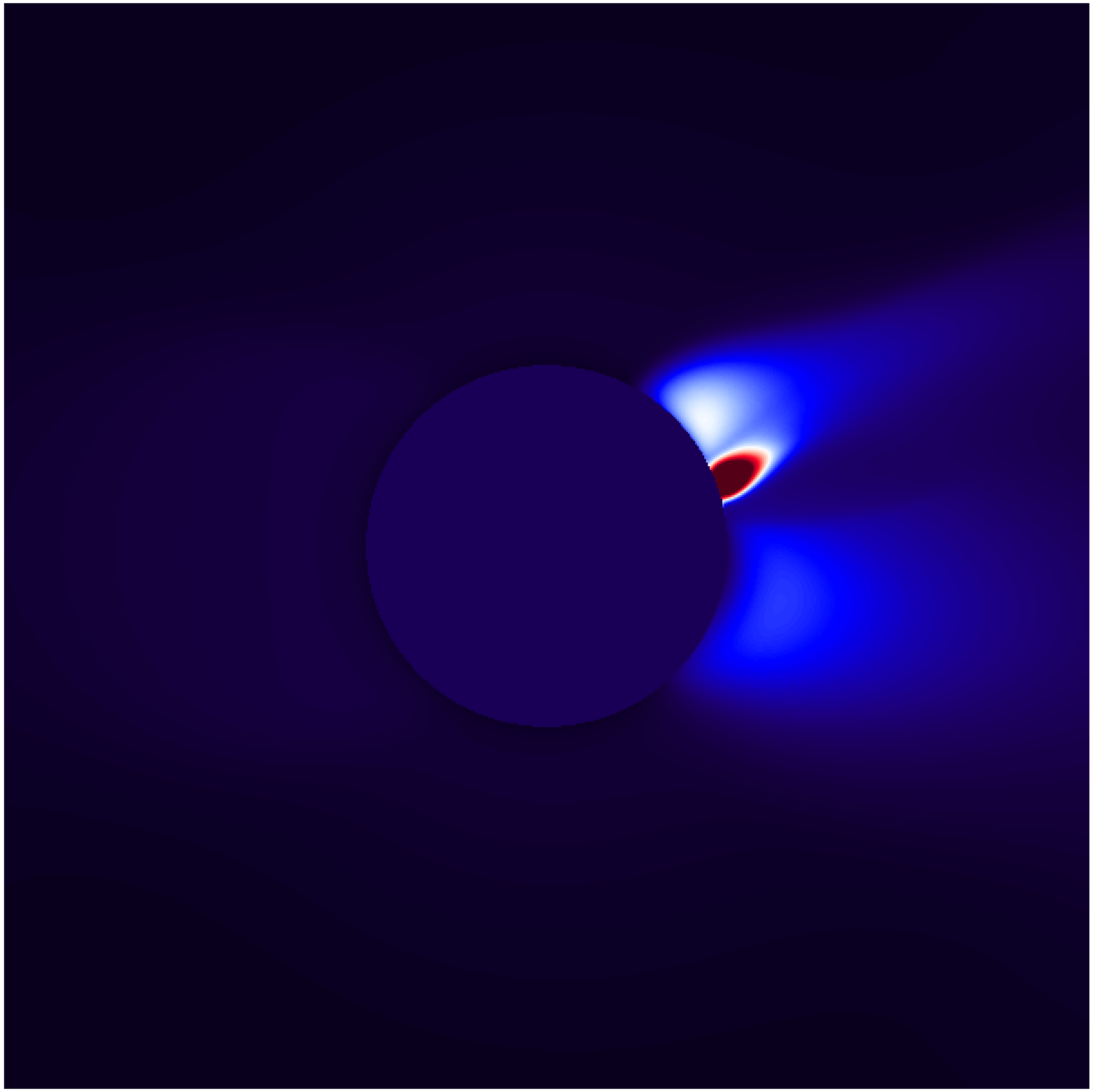
CASE 1A (uniform $\square_o$)
Polarization Brightness



CASE 4
Polarization Brightness



CASE 4
Polarization Brightness



CONCLUSION

- We have made considerable progress in modeling a more realistic field that includes an active region
- Calculations with B ~ 1000 G are possible
- Future work:
  - Better initialization of the plasma pressure and density
  - Application to the observed magnetic field on May 12, 1997
  - Energization of the initial state (with guidance from the constant-α solution of Yang Liu, JASTP, 2004)
  - Explore flux cancellation to disrupt the active region and generate a CME
  - Follow the propagation of the CME in interplanetary space
  - In the future we intend to use actual magnetic field observations (e.g., May 12, 1997)