3D MHD modeling of EIT waves observed by STEREO

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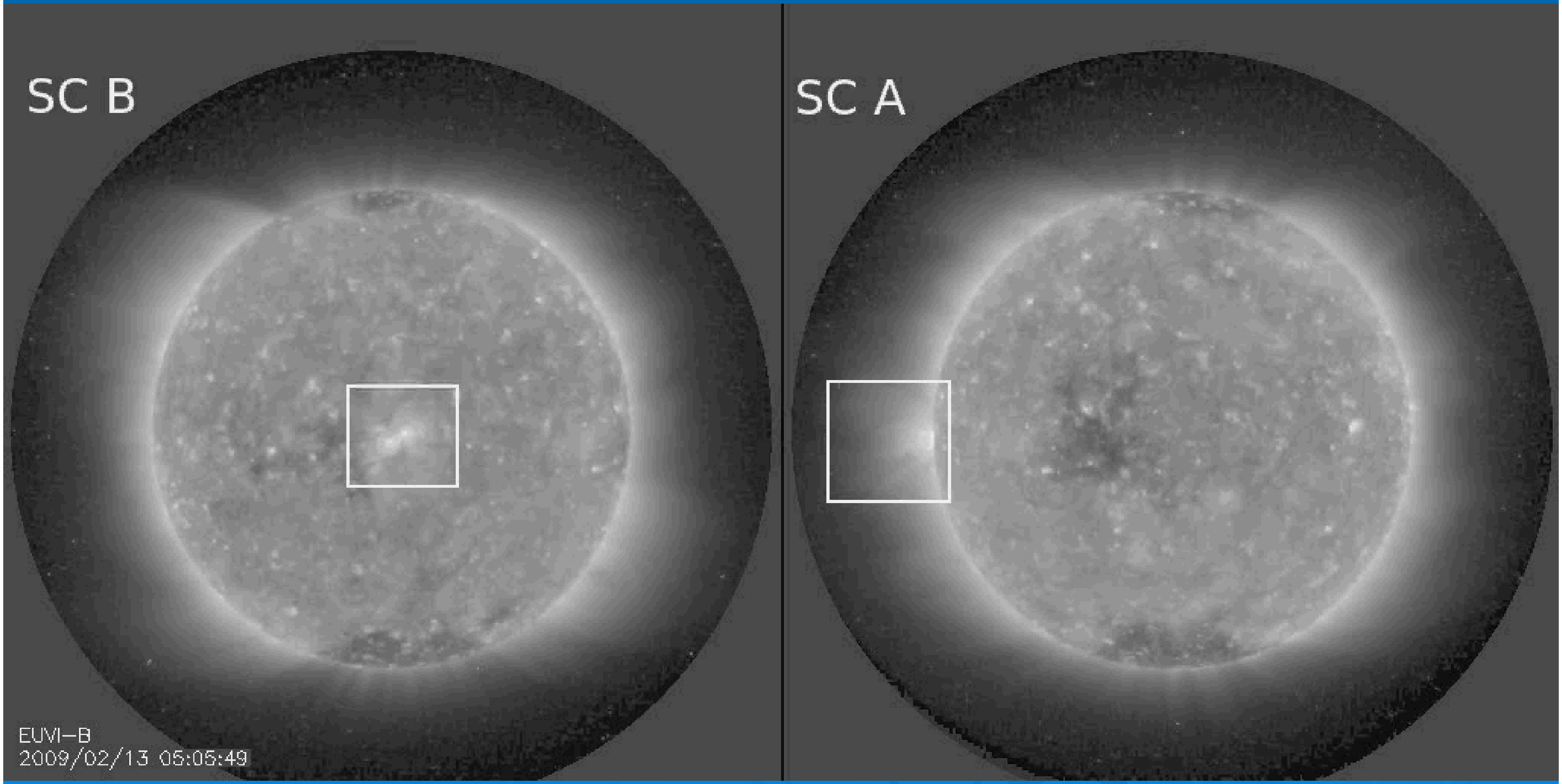
Introduction

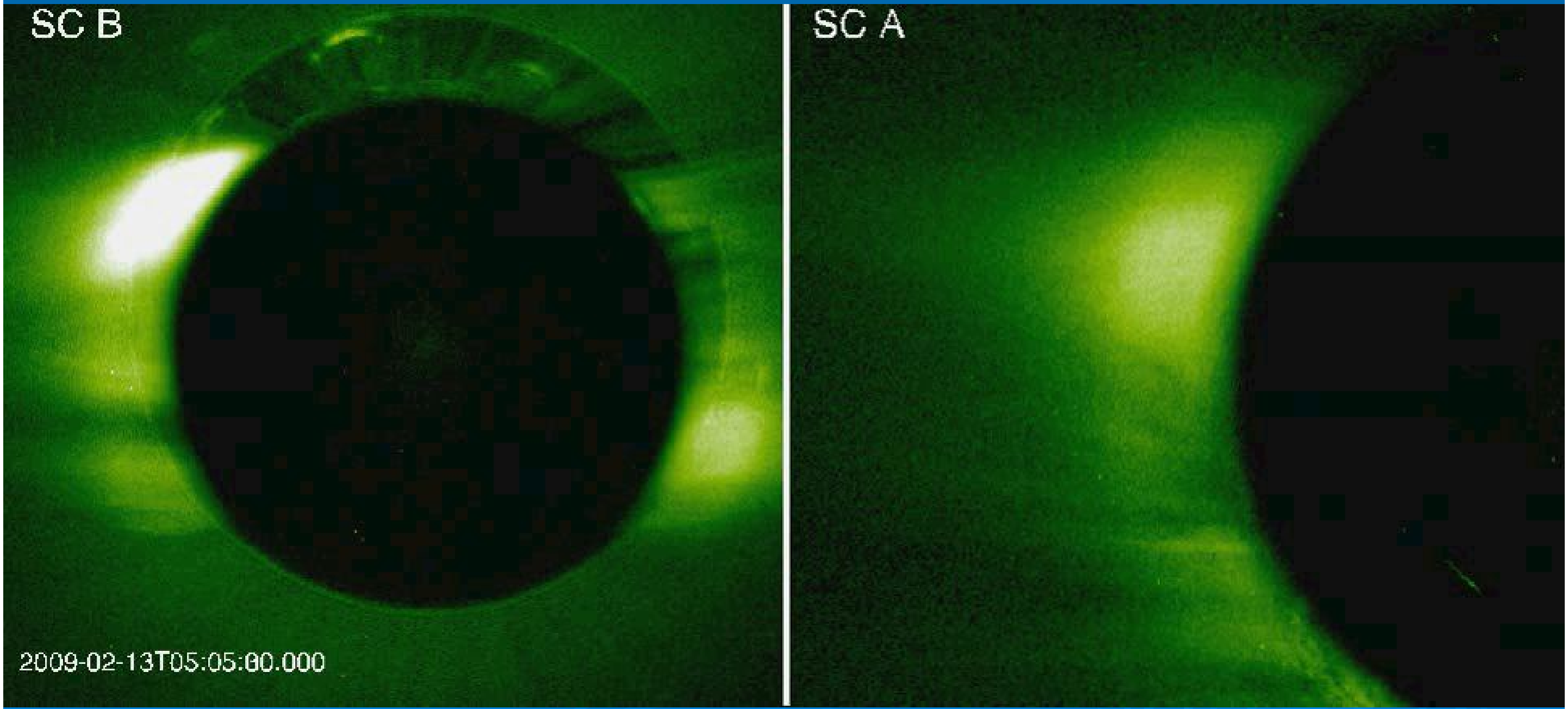
- Large scale coronal waves were first observed by the SOHO EIT (Thompson et al 1999).
- The waves are associated with flares and CME's and propagate at speeds 200-500 km/s.
- These waves were interpreted as fast magnetosonic waves using 3D MHD and STEREO observations (e.g., Wang 2000, Wu 2001, Ofman & Thompson 2002, Patsourakos & Vourlidas 2009).
- Other interpretations in term of CME projection effects, slow shocks, solitary waves were also proposed.
- Here, 3D MHD equations are used to model the propagation and reflection of these waves from coronal holes with application to coronal seismology.

CME/EIT wave in quadrature with STEREO



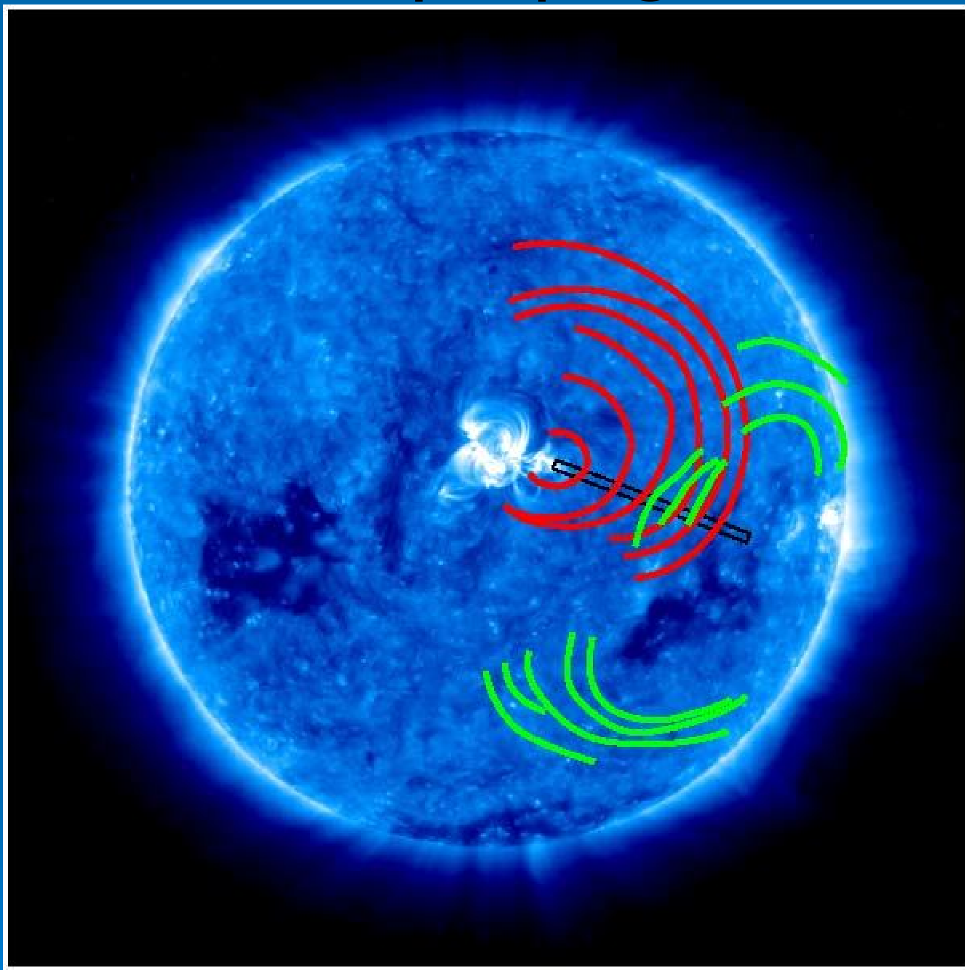
(Patsourakos and Vourlidas 2009)

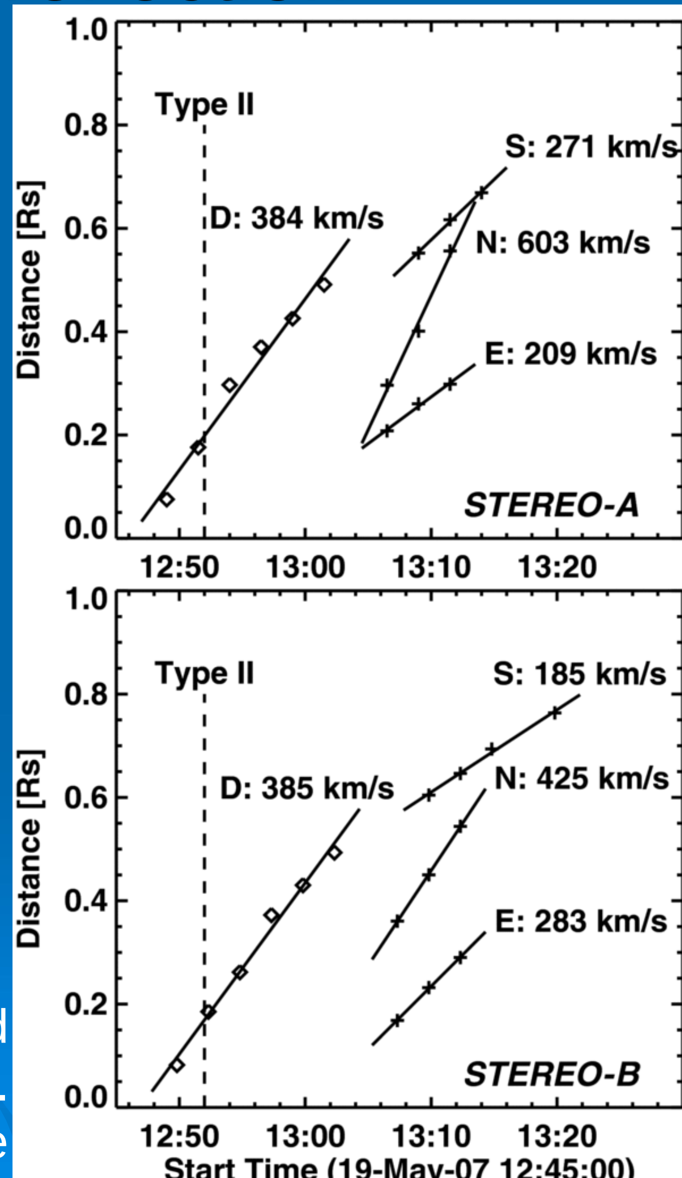
CME/EIT wave in quadrature with STEREO



(Patsourakos and Vourlidas 2009)

STEREO Observations of EIT waves: propagation and reflection



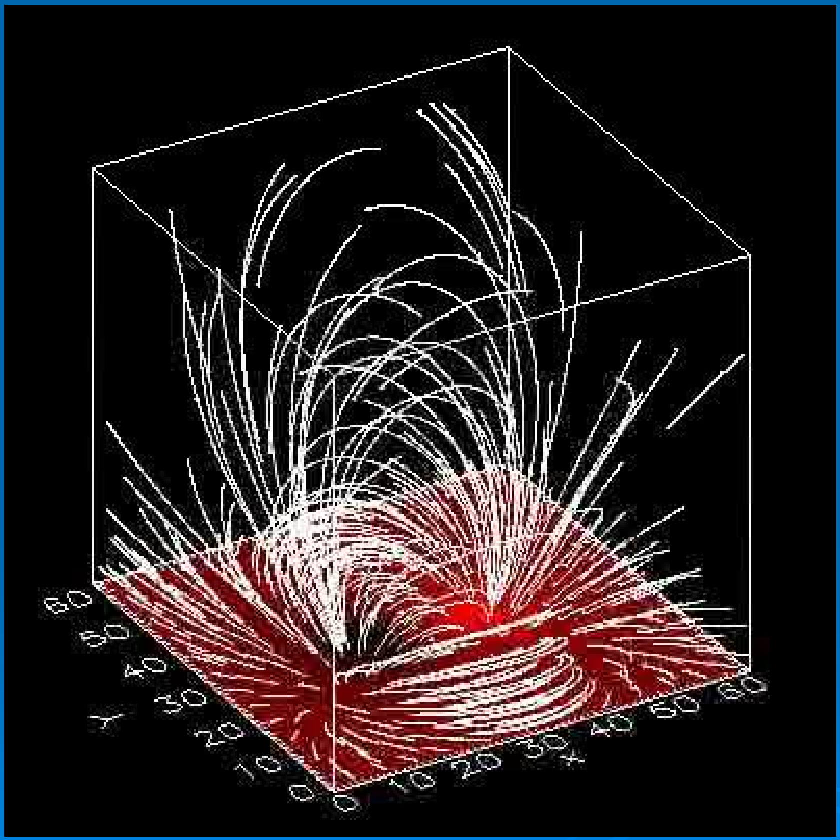


STEREO B EUVI 171: 2007/05/19 12:32:19 and velocities, taken from Gopalswamy et al. (2009). The bright loop feature in the middle is an active region just after the launch of a CME.

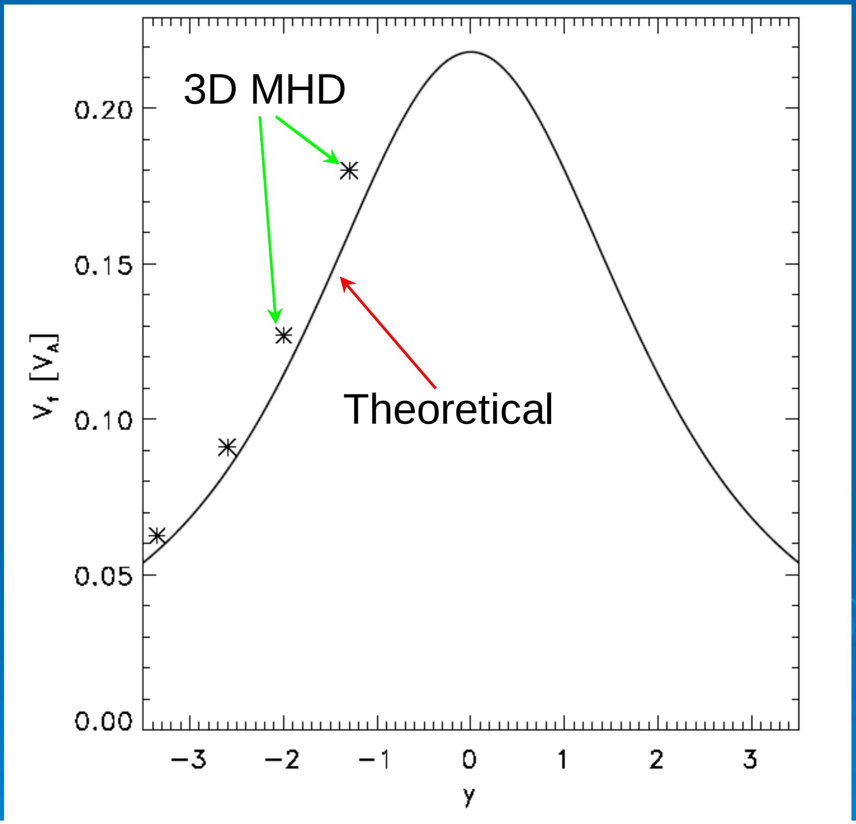
3D MHD model of EIT wave: idealized dipole field

(Ofman & Thompson 2002)

3D MHD model



Fast magnetosonic wave speed

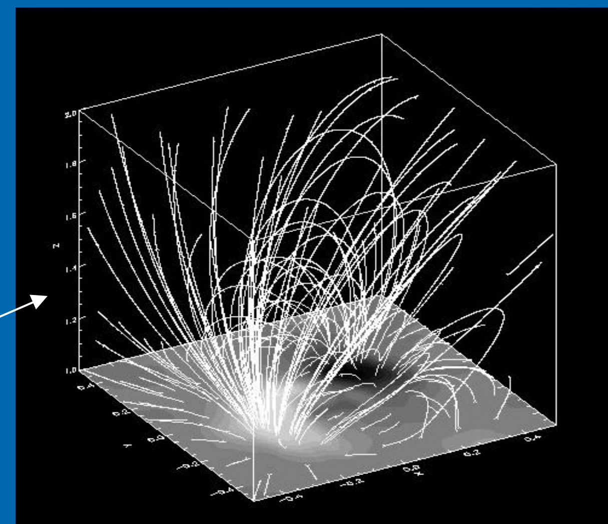


$$V_f = \left(\tfrac{1}{2}\{V_A^2 + C_s^2 + [(V_A^2 + C_s^2)^2 - 4C_s^2 V_A^2 \cos^2\theta]^{1/2}\}\right)^{1/2}$$

Boundary and initial conditions

$$\boldsymbol{B}(x_{\min,\max}, y, z) = \boldsymbol{B}(x_{\min,\max} \pm \Delta x, y, z) \ ,$$
$$\boldsymbol{V}(x_{\min,\max}, y, z) = \boldsymbol{V}(x_{\min,\max} \pm \Delta x, y, z) \ ,$$
$$\rho(x_{\min,\max}, y, z) = \rho(x_{\min,\max} \pm \Delta x, y, z)$$

$$\boldsymbol{B}(x, y, z_{\min}, t) = \boldsymbol{B}_0(x, y, z_{\min}) \ ,$$
$$\boldsymbol{V}(x, y, z_{\min}, t) = 0,$$
$$\rho(x, y, z_{\min}, t) = \rho_0(x, y, z_{\min})$$



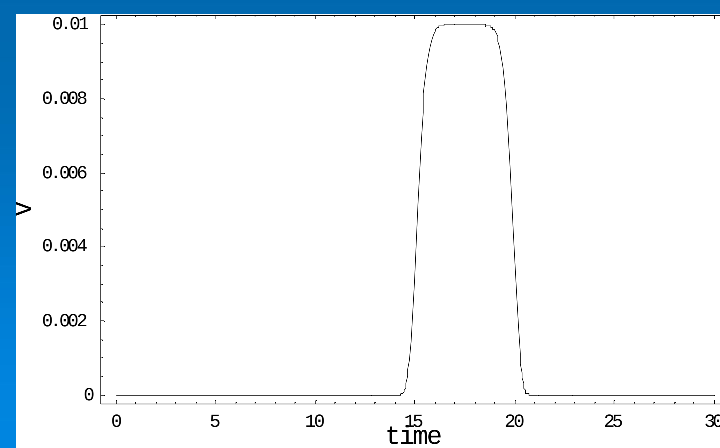
Initial Conditions:
Force free field extrapolation

Hydrostatic density: $N = n_0 \exp\left[\frac{R_s}{H}\left(\frac{R_s}{r} - 1\right)\right]$

where H is the scale height

Initial velocity pulse at the boundary plane:

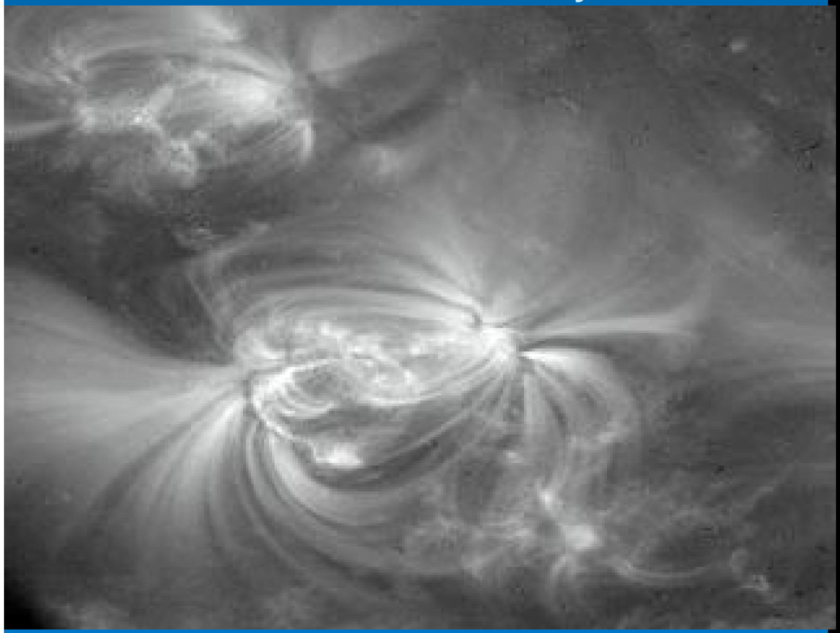
$$V = V_0 \exp\left[-\left(\frac{t - t_0}{\Delta t}\right)^8\right]$$

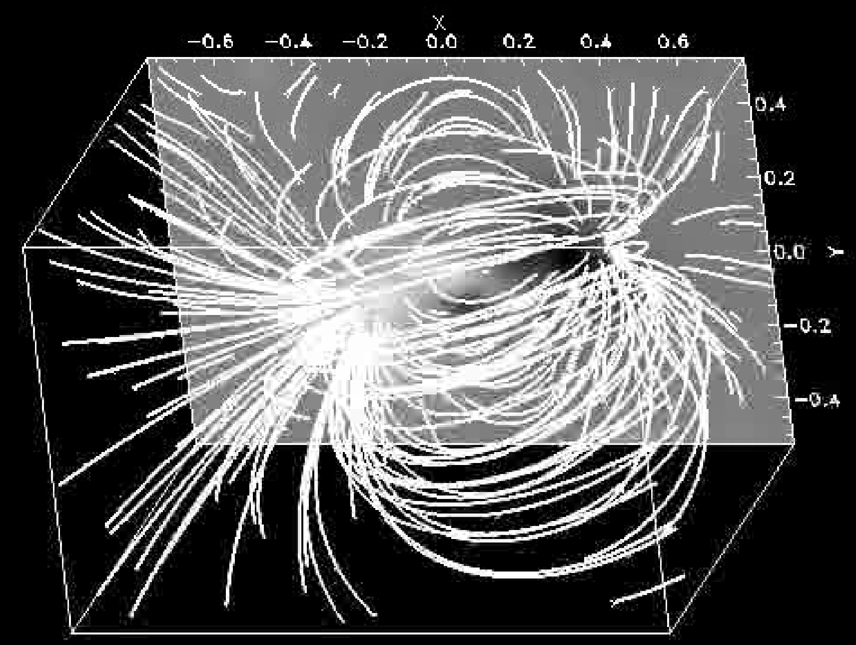


TRACE observations vs. 3D MHD Impact from below

(Ofman 2007)

AR8270: TRACE 171Å, July 14, 1998





3D MHD with photospheric B from Kitt Peak data, and initial pulse in V_z at the location of the flare.

Past studies: Detailed comparison to observations: TRACE/ 3D MHD

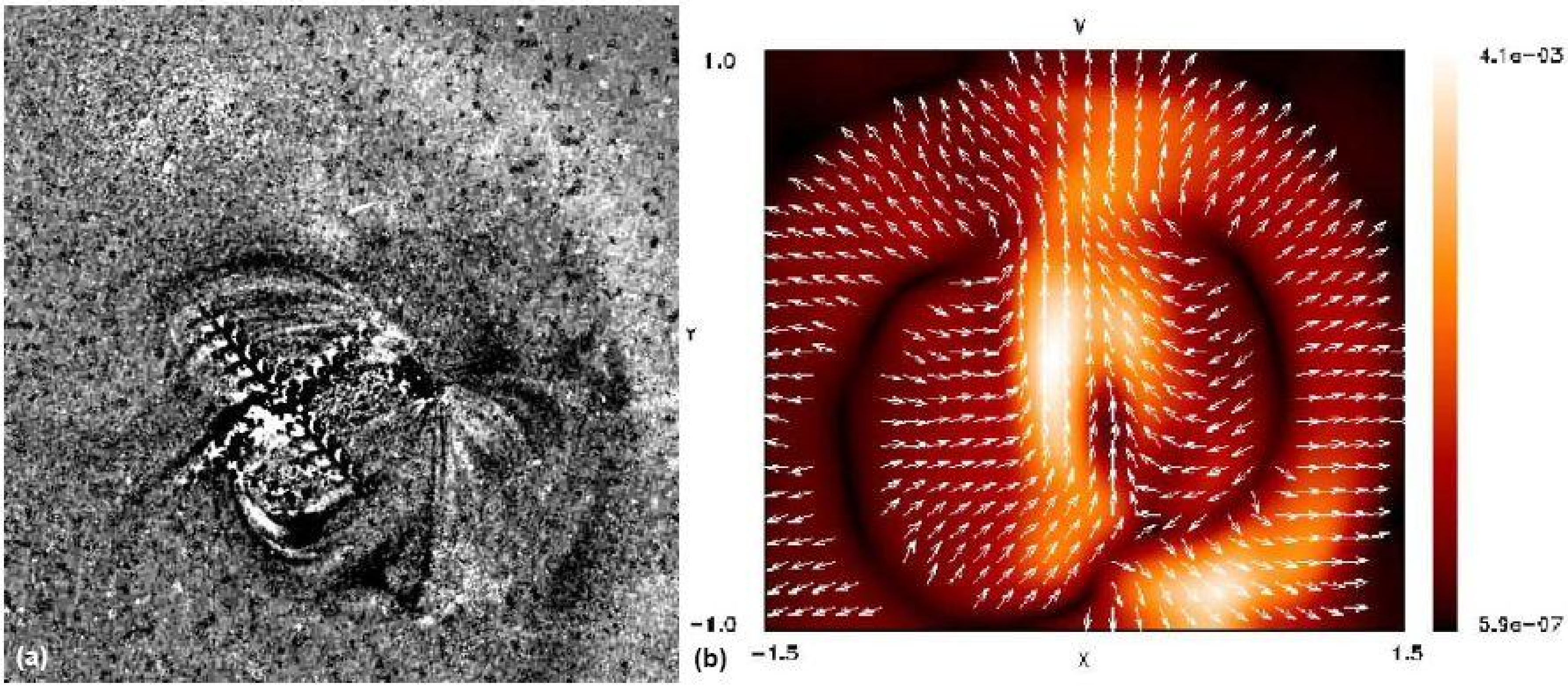
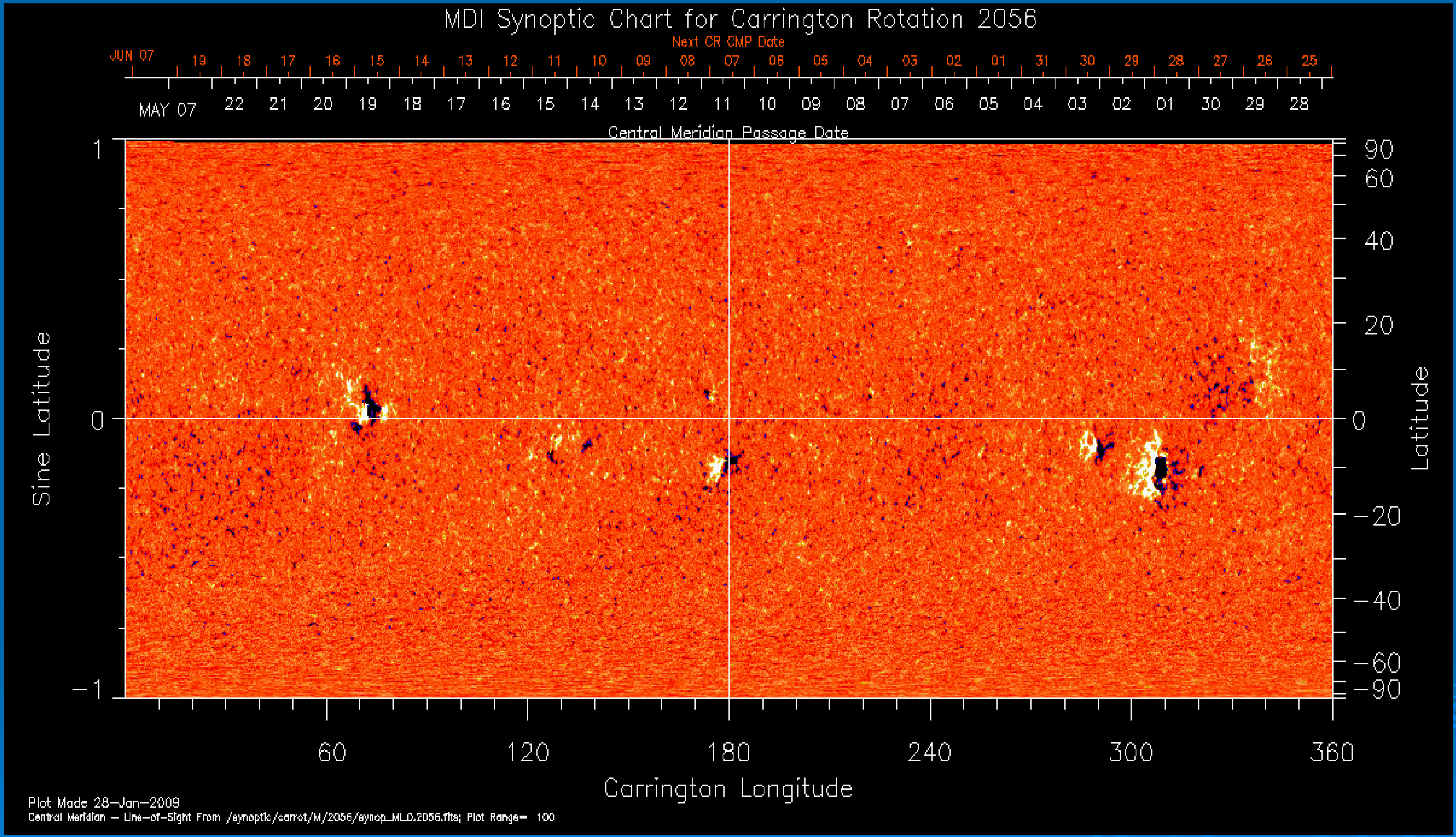


Figure 6: Comparison between an EIT wave observed by TRACE (a), and a density pulse of the same event modeled by NLRAT (b).
Images: (a) Wills-Davey (2007) (b) Ofman (2007)

Present 3D MHD Model

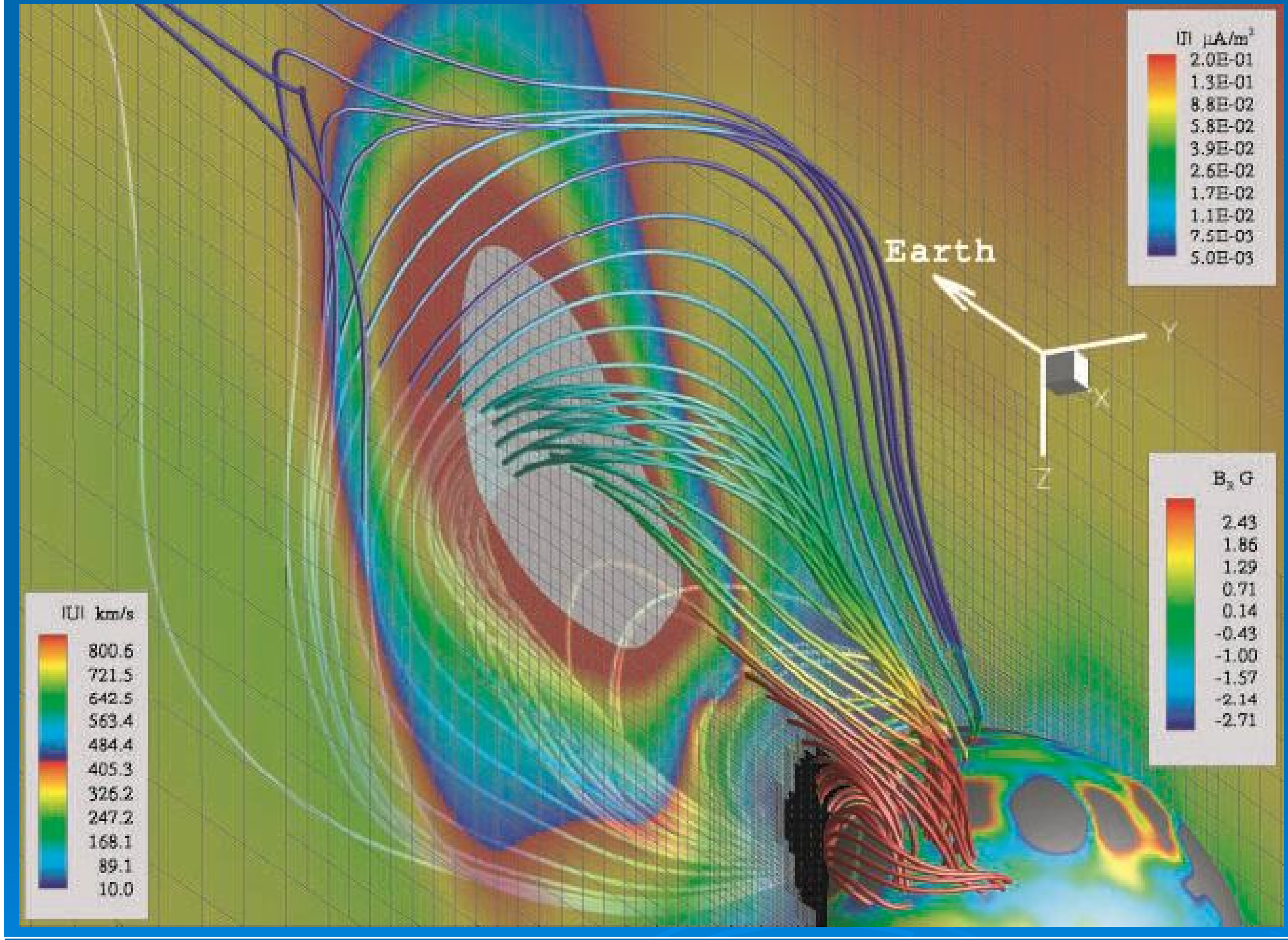
- We use the 3 D BATS-R-US MHD code described in Roussev et al. (2003, 2004) for our simulations.
- This code solves the full time-dependent set of the non-linear ideal MHD equations in 3D.
- We run the code with 128 parallel processors on NASA's supercomputer at AMES.
- The code uses a Riemann solver on a grid of cubic cells. The algorithm includes Adaptive Mesh Refinement (AMR). On average, the grid consists of about 54,000,000 cells, filling a box with one side length of 48 solar radii (R_s) and centered around the Sun.
- The code uses initial solar corona magnetic fields and initial solar wind outflow profiles for velocity and density as boundary conditions to start the simulation. The initial pressure follows an adiabatic law with an empirical radially varying (decreasing) polytropic index, which accounts for a non-adiabatic expansion of the solar wind close to the solar surface.
- The initial fields in the corona is initialized using a potential solar source field extrapolation of the observed photospheric magnetic field.
- After initiation, the code evolves this configuration of the solar corona non-linearly and self-consistently in time. We follow the time evolution of the system over four hours in our simulations.

Solar magnetic field



MDI magnetogram of Carrington rotation 2056. The active region of concern is the leftmost spot close to the equator in the image. For the simulation, however, we use higher resolution data obtained with the Wilcox Solar Observatory.

Onset of CME that triggers the EUV wave



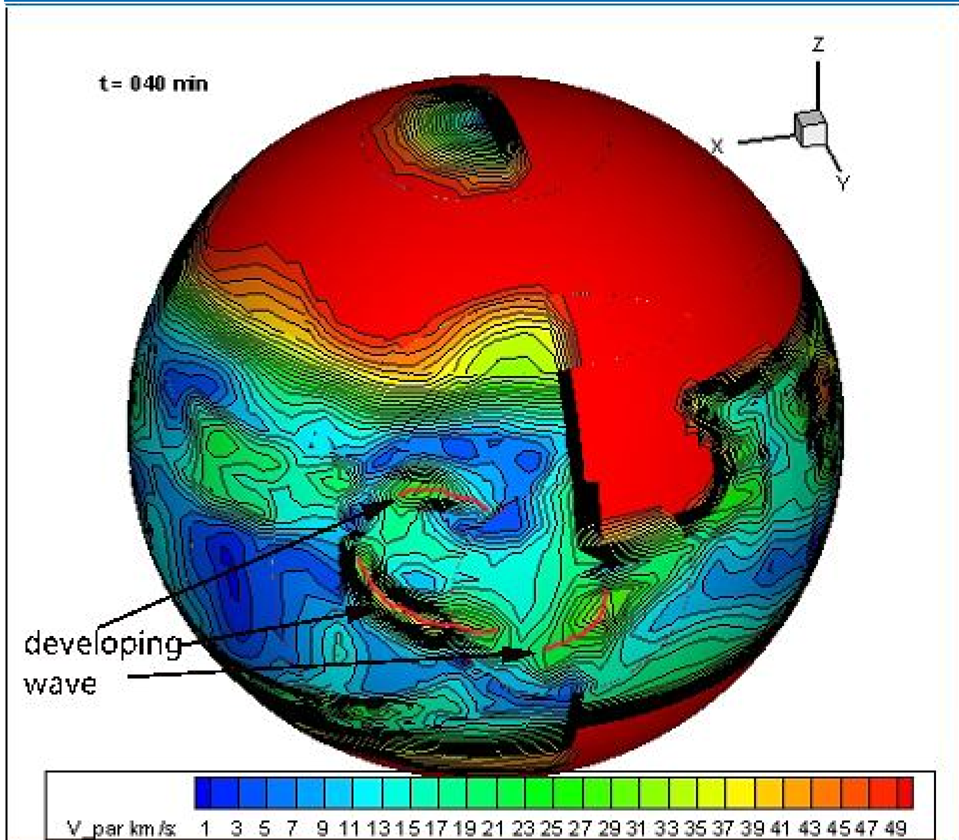
Within the reconstructed fields of the active region, a magnetic flux rope of Gibson and Low (1998) type is introduced for the initial CME.

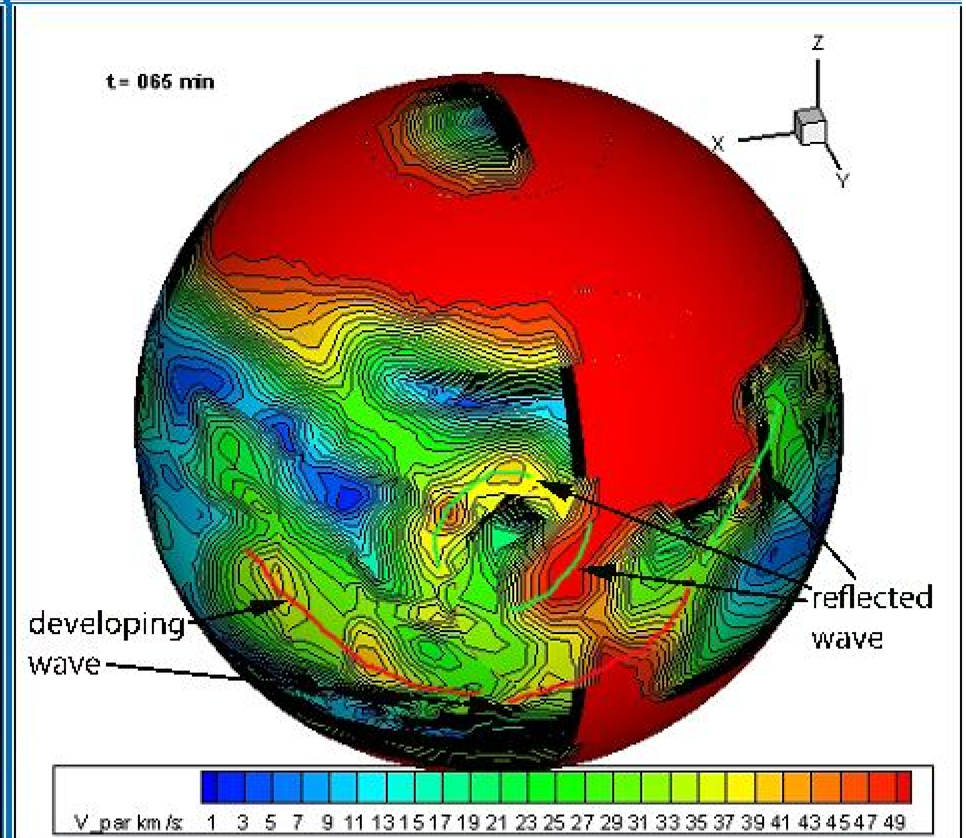
Its dimensions and orientations are chosen such that the resulting eruption matches the observations.

The CME is launched by creating a horizontal velocity shear flow on the solar surface, which severs foot magnetic field lines of the flux rope.

Model results

May 19, 2007 event

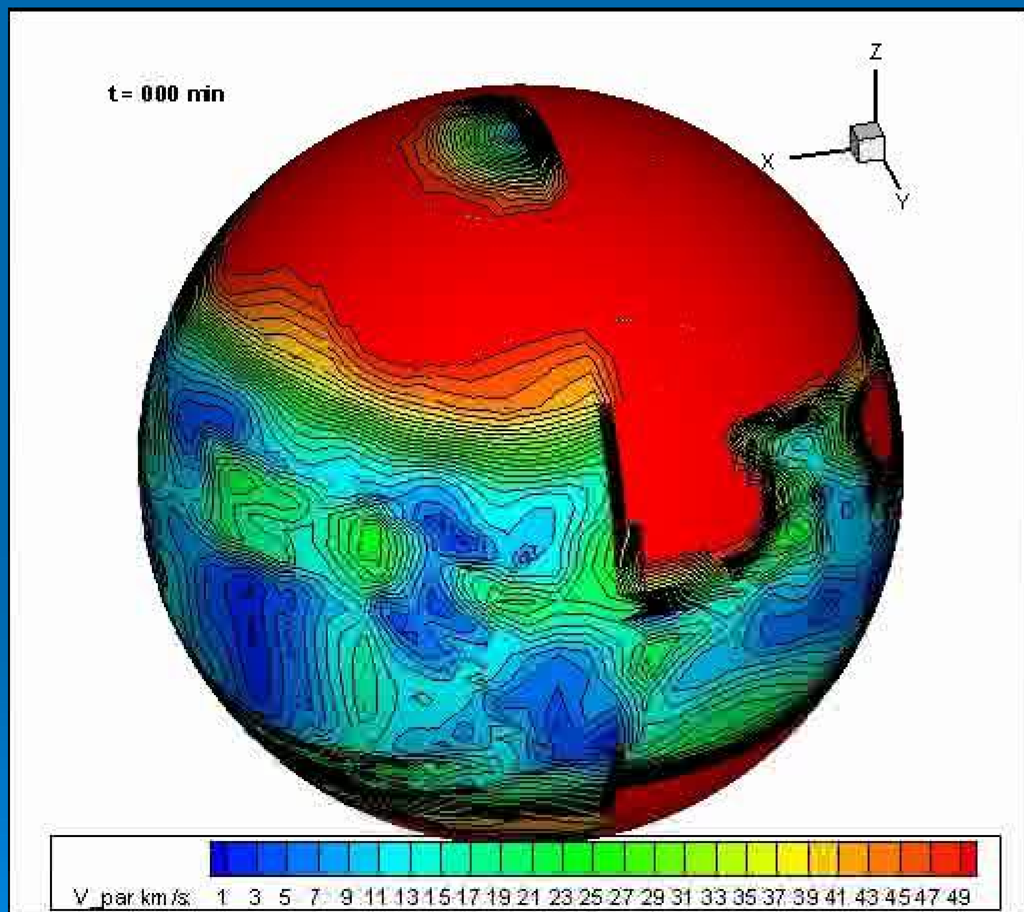




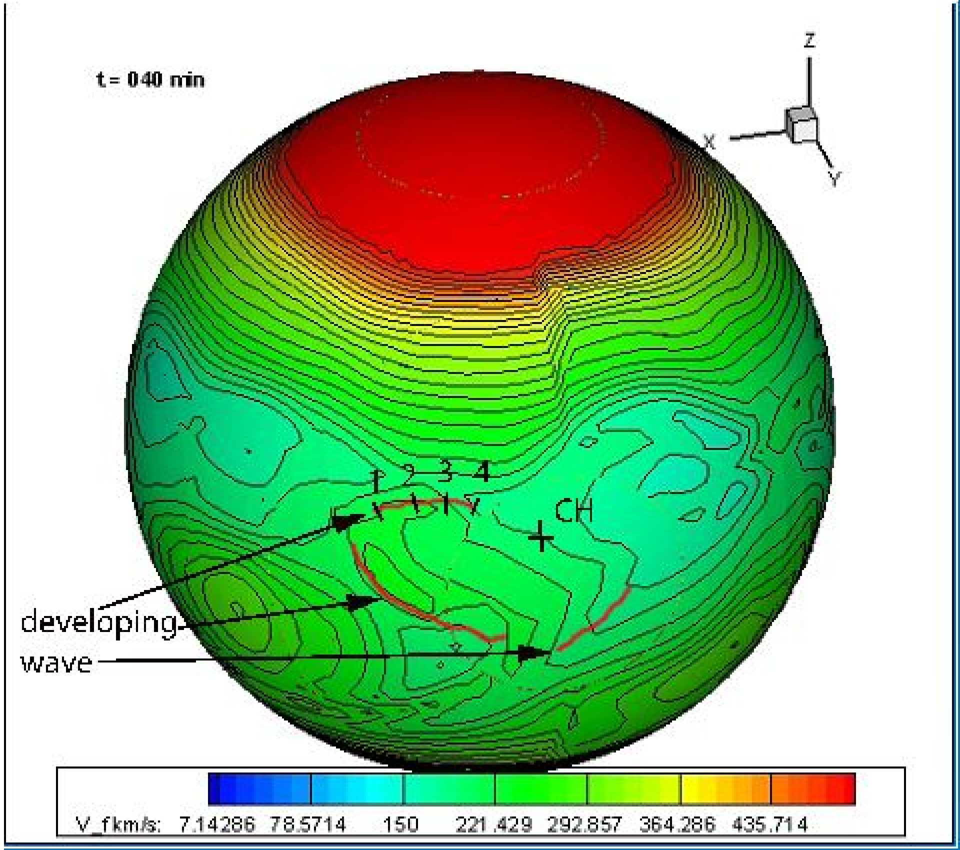
Spherical contour plots of plasma velocity V_{par} parallel to the solar surface at a heliocentric distance of 1.2 R_s. The EIT wave shows up as traveling velocity enhancements in V_{par}. The identified wave fronts (red bars) are centered around an epicenter of the initial launching site of the CME above the active region.

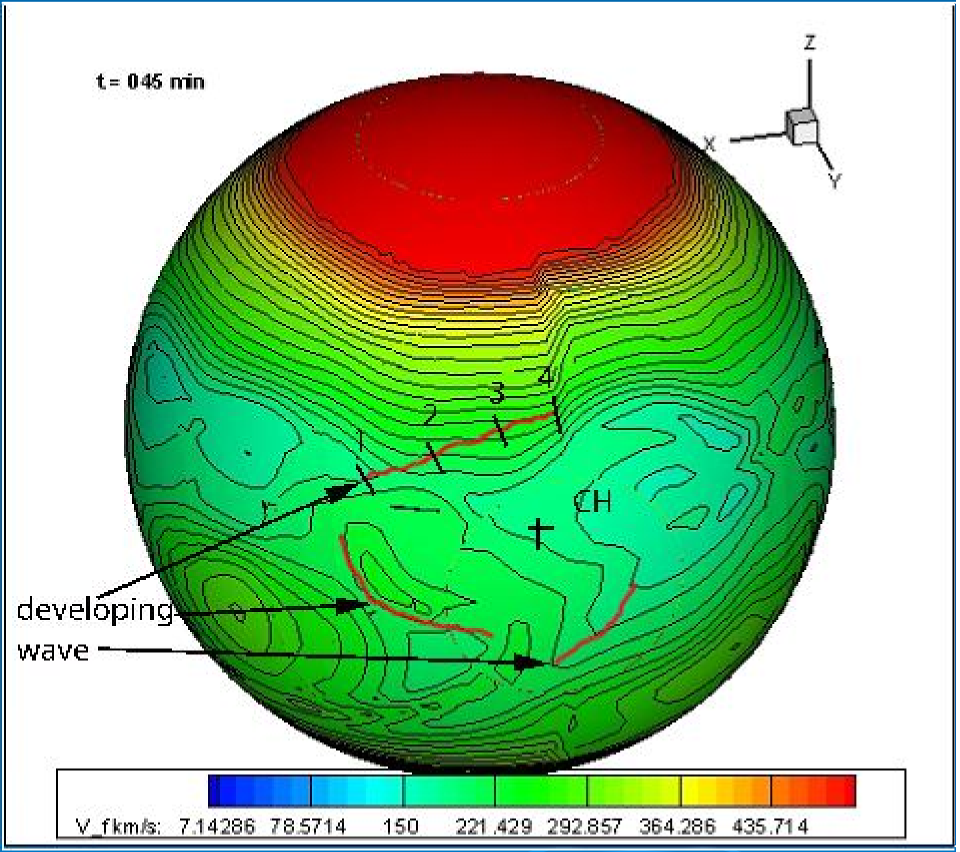
EIT waves animation

May 19, 2007 event



Phase velocities of the EIT wave





Spherical contour plots of the simulated phase velocity V_f of a fast magnetosonic wave at 1.2 R_s heliocentric distance. On the northern wave front we have marked four points. From the displacement of these points we can compute estimates for the phase speeds of this front. The label ``CH'' denotes the center of the coronal hole.

Magentosonic speed

Fast and slow magnetosonic speed:

$$V_{f,s} = \left(\frac{1}{2} \left\{ V_A^2 + C_s^2 \pm \left[\left(V_A^2 + C_s^2 \right)^2 - 4 C_s^2 V_A^2 \cos^2 \theta \right]^{1/2} \right\} \right)^{1/2}$$

Alfvén speed: $V_A = \frac{B}{\sqrt{4\pi\rho}}$

Sound speed: $C_s = \sqrt{\frac{kT}{m_p}}$

In the corona usually: $C_s << V_A \rightarrow V_f \approx V_A$

<u>Coronal seismology with STEREO:</u>

1. Use 3D reconstruction in EUV to obtain ρ(x,y,z) and possibly T(x,y,z)
2. Measure V_{wave}
3. *Use 3D MHD to determine the relation* $V_{wave} \Leftrightarrow V_{f,s}$
4. From V_f obtain B(x,y,z) using ρ(x,y,z) and possibly T(x,y,z)
5. Validate the results with 3D MHD model and improved B, ρ, T.

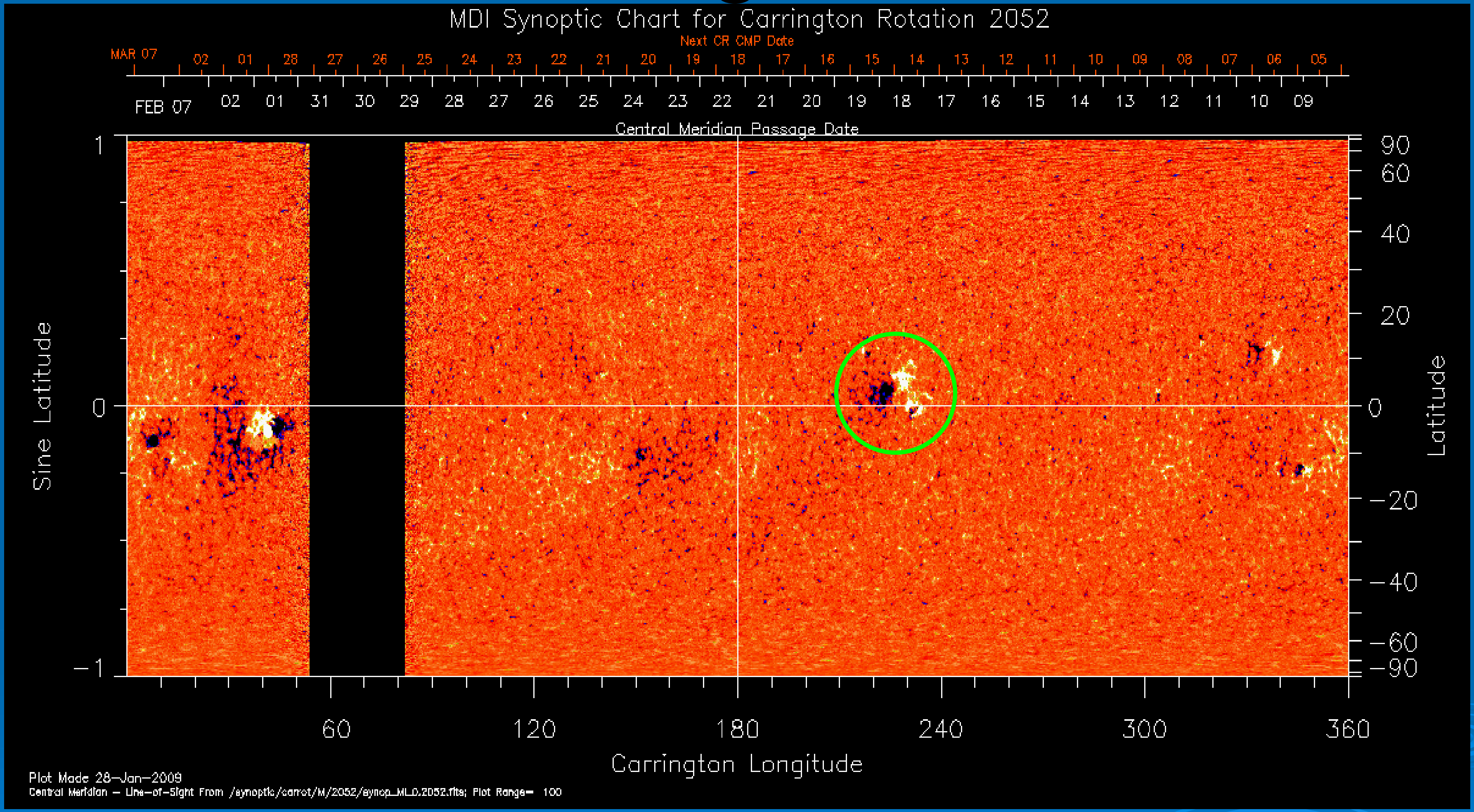
Phase velocities of the EIT wave

Point	Angle [degree]	Meas. Phase Speed [km/s]	Sim. Phase Speed [km/s]	Sim. Fast Mode Speed [km/s]
1	30 ± 2	190 ± 40	152.2 ± 40	197 ± 40
2	40 ± 2	205 ± 40	249.4 ± 40	213 ± 40
3	55 ± 2	230 ± 40	267.0 ± 40	229 ± 40
4	80 ± 2	280 ± 40	296.0 ± 40	244 ± 40

Measured, Simulated, and Fast Mode Phase Speeds, depending on the clockwise position angle from the coronal hole

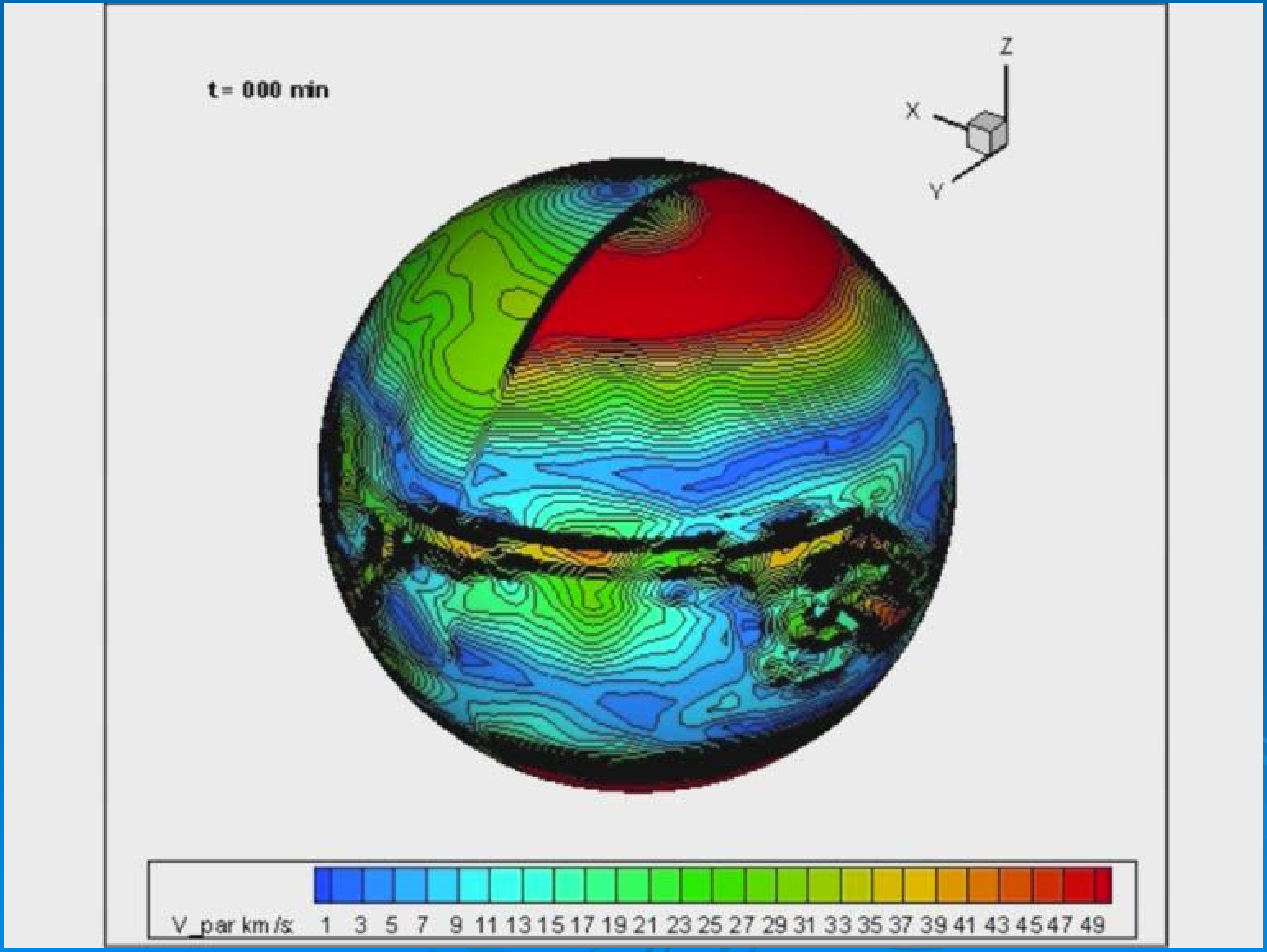
$n=10^8$ cm^{-3} => B~0.9 – 1.3 G

Solar magnetic field



MDI magnetogram of Carrington rotation 2052. The active region of concern is the spot marked with green circle. It belongs to the EIT wave observation of 18 January 2007, which is probably the first observation of a strong event seen with STEREO. For the simulation, we use higher resolution data obtained with the Wilcox Solar Observatory.

EIT wave animation



Conclusions

- We carried out a simulation of the May 19, 2007 EIT wave observation on the Sun obtained with STEREO spacecraft, using a time-dependent nonlinear fully 3D MHD simulation code.
- The simulated EIT wave spreads in circles over the solar surface and is reflected at a neighboring coronal hole. The coronal hole resonates after the impact of the incident wave and sends out secondary EIT waves to the north and south of the coronal hole. The model agrees with the features of the May 19, 2007 EIT wave observation.
- Furthermore, we find a good agreement between the phase speeds of the simulated EIT wave, the phase speeds of an observed EIT wave propagating at the same location, and theoretical phase speeds of a fast magneto acoustic wave as well.
- Thus, we can explain the EIT wave observations in terms of fast magnetosonic waves in the solar corona.
- This confirms further, that a MHD picture of the solar corona is an adequate description of global phenomena. We can use 3D MHD models, initialized with boundary conditions taken from observations, in order to infer plasma conditions and processes in the solar corona, even at those places where observations are not available or difficult to obtain, and for predictive purposes, such as for Space Weather.