THE MAS CODE:
MODELING THE CORONA AND SOLAR WIND

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MAS MODEL HIGHLIGHTS

• MAS has been around for ~ 15 years
• It is built on a rich base of experience in computational physics and the modeling of solar coronal and fusion plasmas
• Features:
  • Time-dependent resistive MHD
  • Incorporation of observed photospheric magnetic field data
  • Evolution of boundary data
  • Coronal and heliospheric components
  • Non-uniform meshes (structured)
  • 3D finite differences in spherical \((r, \theta, \phi)\) coordinates
  • Implicit and semi-implicit time differencing
  • Comprehensive physics model including the solar wind and energy transport (radiation, parallel thermal conduction, heating, and Alfvén waves)
• Has been used to model CMEs
MAS Code Mesh

\[ \theta = \pi \]

\[ \theta = 0 \]

\[ r = R_O \]

\[ r = R_1 \]

- \( A_\phi, v_\phi, J_\phi, p, \rho \)
- \( A_\theta, v_\theta, B_r, J_\theta \)
- \( B_\phi \)
- \( A_r, v_r, B_\theta, J_r \)
\[ \rho, P \]

\[ v_r, A_r, J_r, \psi \]

\[ v_\theta, A_\theta, J_\theta \]

\[ v_\phi, A_\phi, J_\phi \]

\[ B_r \]

\[ B_\theta, E_{\phi b} \]

\[ B_\phi, E_{\theta b} \]
Fig. 3. The potential magnetic field on May 11, 1997 determined from MDI magnetograms and synoptic maps.  (a) A high-resolution MDI magnetogram taken at 01:40UT on May 11 embedded into a high-resolution MDI synoptic map.  (b) A smoothed version of the magnetic field with high resolution in the active region and smoothed fields outside the active region that is appropriate for driving MHD simulations.  (c) Magnetic field lines in the potential field that matches the photospheric field in (b).  (d) A zoom of the field lines in the active region, showing the computational mesh.
THE SEMI-IMPLICIT METHOD

• Only the momentum equation is modified by the addition of the semi-implicit term

• The semi-implicit term is linear, which simplifies inversion

• Symmetric matrices arise from the semi-implicit term ⇒ invert with preconditioned conjugate gradient methods

• The wave terms become unconditionally stable

• The accuracy is comparable to a fully implicit scheme

• The steady-state solutions are not affected

• If Δt falls below the wave CFL limit, method is the same as an explicit method
MAS MODEL HIGHLIGHTS (CONT.)

• Written in FORTRAN 90
• Designed to run on massively parallel computers using MPI
  • IBM/SP3 + SP4 (xlf)
  • Linux & Beowulf (lf95, pgf90, Intel Fortran, pathscale)
  • Mac (Absoft and xlf)
  • SGI/Altix (ifort)
• Mesh decomposition among processors in 3D
• Dynamic allocation allows mesh size and number of processors to be selected at run time
• Restart capability using HDF files (for long runs)
• Many applications and comparisons with observational data (eclipses, IPS, *in situ* solar wind measurements, coronal holes, pB images, current sheet topology and spacecraft crossings, CMEs)
• A rich set of post-processing tools has been developed
MHD EQUATIONS  
(POLYTROPIC MODEL)

\[ \nabla \times \mathbf{B} = \frac{4\pi}{c} \mathbf{J} \]
\[ \nabla \times \mathbf{E} = -\frac{1}{c} \frac{\partial \mathbf{B}}{\partial t} \]
\[ \mathbf{E} + \frac{1}{c} \mathbf{v} \times \mathbf{B} = \eta \mathbf{J} \]
\[ \frac{\partial \rho}{\partial t} + \nabla \cdot (\rho \mathbf{v}) = 0 \]
\[ \rho \left( \frac{\partial \mathbf{v}}{\partial t} + \mathbf{v} \cdot \nabla \mathbf{v} \right) = \frac{1}{c} \mathbf{J} \times \mathbf{B} - \nabla p + \rho \mathbf{g} + \nabla \cdot (\nu \rho \nabla \mathbf{v}) \]
\[ \frac{\partial p}{\partial t} + \nabla \cdot (p \mathbf{v}) = -(\gamma - 1)p \nabla \cdot \mathbf{v} \]

\[ \gamma = 1.05 \text{ in the corona;} \]
\[ \gamma \sim 1.5 \text{ in the inner heliosphere} \]
MHD EQUATIONS
(Improved Energy Transport)

\[ \nabla \times B = \frac{4\pi}{c} J \]

\[ \nabla \times E = -\frac{1}{c} \frac{\partial B}{\partial t} \]

\[ E + \frac{1}{c} v \times B = \eta J \]

\[ \frac{\partial \rho}{\partial t} + \nabla \cdot (\rho v) = 0 \]

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

\[ \frac{\partial p}{\partial t} + \nabla \cdot (pv) = (\gamma - 1)(-p \nabla \cdot v - \nabla \cdot q - n_{enp} Q(T) + H) \]

\[ \gamma = \frac{5}{3} \]
Finding MHD Solutions

• Use line-of-sight magnetograms to deduce $B_r$ from $B_{\text{los}}$ at $r = R_o$ (e.g., Kitt Peak Solar Observatory, Wilcox Solar Observatory, SOHO/MDI synoptic maps)

• Calculate a potential field matching $B_r$ at $r = R_o$

• Specify $T$ and $\rho$ on the solar surface $r = R_o$ (e.g., uniform $T_o$ and $\rho_o$)

• Use characteristic boundary conditions (gas characteristics along $B$) to determine $v$ at $r = R_o$

• Set up $p$, $\rho$, and $v$ from a spherically symmetric solar wind (1D Parker solution)

• Integrate 3D MHD equations in time until steady state is reached

• This gives the structure of the coronal magnetic field $B$ (as well as $p$, $\rho$, $v$, $T$)

• Compare with observations
MHD Model of the Corona and Inner Heliosphere: Overview

Line-of-sight Photospheric Magnetic field (e.g., Kitt Peak)

$B_r$ at inner boundary

Coronal Model

Density, temperature constant

Speed from magnetic topology

Momentum Flux balance => density

Pressure balance => temperature

Heliospheric Model

30 Solar radii – 5 AU

1 – 30 Solar radii

Flux balance => density
Whole Sun Month, Aug. 10 – Sep. 8, 1996

Kitt Peak Synoptic Chart, $B_r$

Smoothed Magnetic Field (used in MHD model)
Whole Sun Month
Aug. 10 – Sep. 8, 1996
Radial Velocity
Open and Closed Field Lines
The Heliosphere During Whole Sun Month
August  September 1996
Polarization Brightness

- Light scattered off the coronal electrons is observed in coronagraphs

\[ pB(x) = K \int_{\text{los}} n_e(x - x') C(r') \, dl' \]

- \( C(r) \) is a scattering function (e.g., Billings 1966)
- To produce a plane-of-sky image, we apply a (radial) filter to \( pB \) ("vignetting function") and we simulate the effect of an occulting disk
MHD Modeling of the Solar Corona During Whole Sun Month

MHD Model, $r = 1.75R_s$

MLSO MKIII, $r = 1.75R_s$

MHD Model, $r = 2.35R_s$

LASCO C2, $r = 2.35R_s$

MHD Model, $r = 5R_s$

LASCO C3, $r = 5R_s$

Coronal Holes

3D MHD Model (Coronal Holes)  NSOKP Coronal Hole Map

EIT Fe XII Image  EIT Fe XV Image

Sources of Solar Wind at the Sun

Measured at Ulysses

North Pole View
Eclipse Comparisons

Field Lines (MHD Model)  Polarization Brightness (MHD Model)  Eclipse Image

November 3, 1994

October 24, 1995

March 9, 1997

February 26, 1998

August 11, 1999
Solar Wind Velocity in the Heliosphere During Whole Sun Month (August September 1996)

Radial Velocity in Equatorial Plane

Radial Velocity in Meridional Plane

Radial Velocity at $r = 1$ AU

Radial Velocity at $r = 4.2$ AU

km/s

300 400 500 600 700
Whole Sun Month 3
Aug. 18–Sep. 14, 1999

Kitt Peak Synoptic Chart, $B_r$ (Carrington Rotation 1953)

Smoothed Magnetic Field (used in MHD model)
EUV Emission

- The emission in the corona is dominated by collisional excitation from electron impact, so that the apparent emission rate is

\[ R_{EUV} \propto \int \text{los} n_e^2 f(T) \, dl, \]

where \( f(T) \) is a (known) function that depends on coronal ion abundances, the line being observed, and the properties of the observing instrument (e.g., the Fe XII 195Å line for EIT)
Quantitative Comparison Between Observed and Computed Coronal Emission
SOHO/EIT and Yohkoh/SXT Observations on August 27, 1996

SOHO/EIT and Yohkoh/SXT Observations on August 27, 1996

MHD Simulation
Comparing Emission from a Force-Free Magnetic Field Model with Observations of AR7986 on August 29, 1996

Simulated 171Å Emission  Simulated 195Å Emission  Simulated 284Å Emission

Observed EIT 171Å Emission  Observed EIT 195Å Emission  Observed EIT 284Å Emission
**INPUTS/OUTPUTS**

- **Inputs:**
  - A sequence of synoptic magnetic field maps (Kitt Peak, WSO, Mt. Wilson, MDI)
  - Polytropic: base temperature and density
  - Improved energy model: coronal heating distribution, Alfvén wave flux at base

- **Outputs:**
  - $B(x), v(x), T(x), n(x)$
  - Field line traces, mapping, and connectivity
  - Field line structure and topology ($K, Q, \text{coronal hole maps}$)
  - Coronal hole maps
  - Heliospheric current sheet
  - Polarization brightness
  - EUV and X-ray emission
  - Alfvén and sound speed
TYPICAL RUN TIMES

- A low resolution run (with $71 \times 71 \times 64$ mesh points) takes several hours on a single-CPU machine
- An intermediate resolution run (with $101 \times 101 \times 128$ mesh points) takes several days on a single-CPU machine
- An intermediate resolution run takes many hours on a 64-CPU Beowulf cluster
- A high resolution run (with $200 \times 200 \times 300$ mesh points) takes several days on a supercomputer with 1000 processors
CAPABILITIES

• **Present:**
  • Uses longitudinal magnetograms
  • Polytropic model (coronal + heliospheric)
  • Improved energy equation model
  • Flux evolution

• **Future:**
  • Incorporating vector magnetograms
  • Refinement of coronal heating specification (ongoing)
  • Two-temperature model (long term)
USING A SEQUENCE OF VECTOR MAGNETOGRAMS

• Boundary tangential electric field (definition):

\[
E_t = \nabla_t \times (\Psi \hat{n}) - \nabla_t \Phi
\]

• Evolution of the normal boundary magnetic field, \( B_n \):

\[
\frac{1}{c} \frac{\partial B_n}{\partial t} = -\hat{n} \cdot \nabla_t \times E_t = \nabla_t^2 \Psi
\]

⇒ A sequence of magnetograms can be used to determine \( \Psi \)

• Evolution of the normal boundary current density, \( J_n \):

\[
\frac{\partial \Phi}{\partial t} = \frac{\eta}{\tau_{RC}} \left( J_n^o - J_n \right)
\]

where: \( l \) is the scale length of the active region (input)
\( \tau_{RC} \) is the R–C time for the capacitor controlling the current source \( J_n^o \) (input)

\[
J_n^o = \frac{c}{4\pi} \hat{n} \cdot \nabla_t \times B_t
\]

is deduced from a sequence of vector magnetograms