3D MHD Simulation of a CME
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Abstract
We present results from the simulation of a coronal mass ejection (CME) near a large coronal hole for the period of April 21 to May 18, 2005. Observational evidence suggests that the open field lines from a coronal hole can deflect a CME from its initial trajectory. Boundary conditions were established using a magnetogram corresponding to Carrington Rotation 2029. We launched the CME from active region 0758 using the Space Weather Modeling Framework with a background solar wind driven by Alfvén waves that includes the effects of surface Alfvén wave dissipation. We follow the propagation from the lower corona out to approximately 4.5 solar radii. We find that the presence of the CME induces curvature in the open field lines of the coronal hole and investigate the resulting magnetic tension and magnetic pressure as drivers of the CME deflection and rule out reconnection as a cause. Treating the CME as a rigid body affected by forces from the coronal hole magnetic field lines we expect a deflection of 40° and we observe a deflection of 23° in the XY plane. We then look at the radial derivative of the Burlaga theta to obtain a better estimate of the CME position. Using the we calculate a position in latitude and longitude and see approximately 20° deflection in each over a 25 minute period.

The Simulation
- Active region 0758 from Carrington Rotation 2029 (April 21- May 18 2005)
- Near a large coronal hole (Fig. 4)
- SWMF with modified TD flux rope including sub-photospheric changes
- 9.18 million cells
- Grid refined near CME path and coronal hole with smallest cell size 3/128 R_i (Fig. 1)
- Start at base of corona (1.035 R_i) and follow for 40 minutes (92500 steps) to 4.5 R_i

Calculating Curvature
- Force per volume from magnetic tension: \[ \frac{B^2}{8\pi} \]
- k is the curvature (one over the radius of curvature)
- Force strongest when field lines most tightly curved
- Curvature calculated using Frenet equations which relate curvature and torsion to the normal, tangent and binormal vectors of a parameterized curve

\[ \kappa = \frac{\left| \mathbf{n} \times \mathbf{t} \right|}{\left| \mathbf{r} \right|} \]
\[ \kappa = \frac{\left| (x' y'' - y' x'') \right|}{(x^2 + y^2 + z^2)^{3/2}} \]

Average curvature calculated for the curving portion of each line at each time step (Fig. 2 top left)
Calculating Force
- Multiply tension term by length of curve to get a force per area (Fig. 2 top right)
- Comparing SOHO images and the simulation we estimate the area of the coronal hole as 10^10 solar radii squared (Fig. 4)
- Use coronal hole to get a force which we equate to a change in momentum at each time step
- Change in momentum divided by CME mass gives change in velocity (Fig. 2 bottom left)
- Averaging 18 field lines results in a final deflection velocity of 584 km/s for a 10^10 g CME

Calculating a Change in Velocity
- Look at simulation CME at 10 minutes (when most of deflection has occurred)
- Estimate mass to be 3x10^15 g and a propagation velocity of ~500 km/s
- Using the estimates from the coronal hole lines we expect a deflection velocity of 183 km/s
- Calculate an expected deflection angle of 20°
- Determine deflection angle by the position of the CME nose defined by an isosurface of temperature (Fig. 3)
- Observe a deflection of 23° in the XY plane between 4 and 10 minutes into the simulation

Calculating Force
- Force per volume from magnetic tension: \[ \frac{B^2}{8\pi} \]
- Force per volume from magnetic tension and magnetic pressure as drivers of the CME deflection
- Using the estimates from the coronal hole lines we expect a deflection of 20°
- Multiply tension term by length of curve to get a force per area (Fig. 2 top right)
- Force per volume from magnetic tension

Comparing SOHO images and the simulation we estimate the area of the coronal hole and investigate the resulting curvature calculated for the curving portion of each line at each time step (Fig. 4). We then look at the radial derivative of the Burlaga theta to obtain a better estimate of the CME position. Using the we calculate a position in latitude and longitude and see approximately 20° deflection in each over a 25 minute period.

Burlaga Theta
- Needed a better method of determining the CME location
- Using Burlaga Theta \[ \theta_B = \frac{1}{R_i} \]
- Describes the amount of the magnetic field in a given direction
- Different regions (CME, Sheath, shock) should have different angles
- Angle not necessarily uniform in a given region but should see a change between regions
- Look at the derivative wrt radius
- At t=0 we can find the flux rope using the current \[ \text{SWMF} \]
- Dissipates current quickly so this only works for t<0
- Match isosurfaces of current and the derivative of theta (Fig. 4)

Analyzing the Derivative
- Want to be certain we are capturing the boundary between the CME and the sheath
- Isosurface at t<0 looks reasonable but look at 2D cut and a line cut through the nose of the CME (Fig 5) as well

Preliminary Position Analysis
- Take the slices from y and z and put into IDL
- Only keep data points from regions where the derivative has a value larger than 75
- This extracts the sheath but we are interested in the CME pause which is the back of the sheath
- Calculate a central position angle (CPA) which is the average of the position angles of the two edges
- Calculate the CPA for each time step to track the position of the CME (Fig. 6)
- \( y \)-cuts for latitude, \( z \)-cuts for longitude

Conclusions and Further Work
- The CPA moves away from the coronal hole
- Sire a jump in the CPA position around the same time as the peak curvature which supports magnetic tension as a cause of deflection
- Need to analyze the abrupt jump in latitude
- Expand to other CMEs
- Different properties and characterize the magnitude of deflection

Fig 1. The magnetic field lines coming from the coronal hole at 4 minutes (left) and 10 minutes into the simulation. The field lines curve as the CME propagates out from the Sun.

Fig 2. The top left shows the curvature over time for a single field line. The top right shows the resulting force per area calculated from the curvature and the bottom left shows the change in velocity this would correspond to for a 10^10 g CME.

Fig 3. The initial guess at the CME location is shown with an isosurface of temperature (in purple). The left image is from 4 minutes into the simulation and the right image from 10 minutes into the simulation.

Fig 4. The left image shows an isosurface of current (in red) as well as an isosurface of the theta derivative (translucent blue) at time t<0. The right image shows an isosurface of the theta derivative. The mostly green ball is an isosurface at 1.04 solar radii colored according to the radial magnetic field with white lines showing contours of density. With this the blue and red pairs show the active regions and the contours are (mostly) coronal holes.

Fig 5. The left image shows color contours of the radial derivative of theta. Several magnetic field lines are traced. The right image shows the derivative, the magnetic field and the density for a line cut through the nose of the CME. Both images are for 10 minutes.

Fig 6. The top image shows the latitudinal CPA over time derived from the radial theta derivative in the 2D slices. The bottom image shows the same for longitude.

References

Initial Estimation of Deflection in the Simulation
- Look at simulation CME at 10 minutes (when most of deflection has occurred)
- Estimate mass to be 3x10^15 g and a propagation velocity of ~500 km/s
- Using the estimates from the coronal hole lines we expect a deflection velocity of 183 km/s
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