Predicting Deflections of Coronal Mass Ejections Using ForeCAT
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Abstract
The accurate prediction of the path of coronal mass ejections (CMEs) plays an important role in space weather forecasting, and knowing the source location of the CME does not always suffice. During solar minimum, for example, solar coronal holes (CHs) can deflect high latitude CMEs toward the ecliptic, and when CHs extend to lower latitudes deflections in other directions can occur. To predict whether a CME will impact Earth, the effects of the background on the CME’s trajectory must be taken into account. We develop a model, ForeCAT (Forecasting a CME’s Altered Trajectory), of CME deflection close to the Sun where magnetic forces dominate. ForeCAT includes CME expansion, a three-part propagation model, and the effects of drag on the CME’s deflection. Given the background solar wind conditions, the launch site of the CME, and the properties of the CME (mass, final propagation speed, initial radius, and initial magnetic strength), ForeCAT predicts the deflection of the CME due to magnetic forces. For a background where the CME is launched from an active region located between a CH and streamer region, the strong magnetic gradients cause a deflection of 39.6° in latitude and 22.6° in longitude for a 10^16 g CME propagating out to 1 AU. ForeCAT does not include the effects of variations in the background solar wind speed or interactions with other CMEs, which could cause additional deflection. ForeCAT can also be used to better understand the space weather in extrasolar planetary systems. Magnetic deflection will play an important role in M stars that have strong magnetic fields that exceed those of Sun.

The Model ForeCAT: Forecasting a CME’s Altered Trajectory

- Combine new analytic model for magnetic deflection with existing analytic and empirical models to describe the path of a CME
- CME input parameters determined from observations
- ForeCAT calculates deflection within a “deflection plane” defined using magnetic gradients and initial CME position
  - Contains maximum deflection
  - Sum forces on edges of CME cross-section within deflection plane
  - Ignore non-magnetic sources of deflection
- No interactions with other CMEs, varying background solar wind speeds or reconnection

ForeCAT Model Details

- Use both components of Lorentz force (JxB) to calculate deflection
- Magnetic Tension
  \[ F_{\text{tension}} = \frac{k B^2}{4\pi} \]
- Magnetic Pressure Gradients
  \[ F_{\text{grad}} = -\frac{\nabla \cdot B^2}{8\pi} \]

Propagation
- Three-part propagation model similar to that of Zhang 2001
  - Slow rise - assume a constant velocity until 1.5 Rs
  - Rapid acceleration - linear acceleration between 1.5 Rs and 3 Rs
  - Propagation - assume constant radial propagation beyond 3 Rs

Expansion
- Use hydrodynamic solution for expanding overpressure region but replace thermal overpressure with magnetic overpressure similar to Melon-Seed-OverExpansion model of Sicves 2006

Drag
- Expect interaction between radially outflowing solar wind and CME → CME’s deflection motion should be impeded by drag force
- Effects of radial drag already incorporated into empirical propagation model so do not explicitly calculate radial drag

Magnetic Field Model
- Use steady state solar wind results from an magnetohydrodynamic simulation (Space Weather Modeling Framework - Toth 2011)
- Take results from ring at 1.15 Rs within deflection plane and fit polynomial
- Scale to other radii using r

Sampling Parameter Space
- Vary two input parameters and hold all others constant to explore parameter space

ForeCAT Results

Test Case
- Input parameters: mass 10^16 g, final propagation velocity 475 km s^-1, cross-sectional radius 0.15 Rs, and internal magnetic field 10 G

a. Trajectory of CME below ~10 Rs: the line represents the diameter of the circular cross-section parallel to the y-axis so the figure shows both the position and size of the CME
b. Central position angle of the CME out to 1 AU: the majority of the deflection occurs before 3 Rs and the CME maintains a relatively constant position out to 1 AU. CME deflects 44.9° → 39.6° in latitude and 22.6° in longitude

Sampling Parameter Space
- Vary two input parameters and hold all others constant to explore parameter space

Trends for input parameters:
- More massive CMEs deflect less
- Below 5x10^15 g faster CMEs deflect less
- CMEs with more expansion deflect less
- Initially large cross-sectional radius have less deflection

Our newly developed model, ForeCAT, predicts the trajectory of a CME away from the Sun. Sets of ForeCAT runs covering a wide range in input parameter space produce a range of possible deflections from a given source location, which could prove useful for space weather forecasting as well as insights into the space weather of extrasolar planetary systems. ForeCAT produces results on the order of minutes, faster than the 2-5 days a CME typically takes to travel to 1 AU.

References