Constraining CME Models using STEREO data for Space Weather Predictions

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Abstract

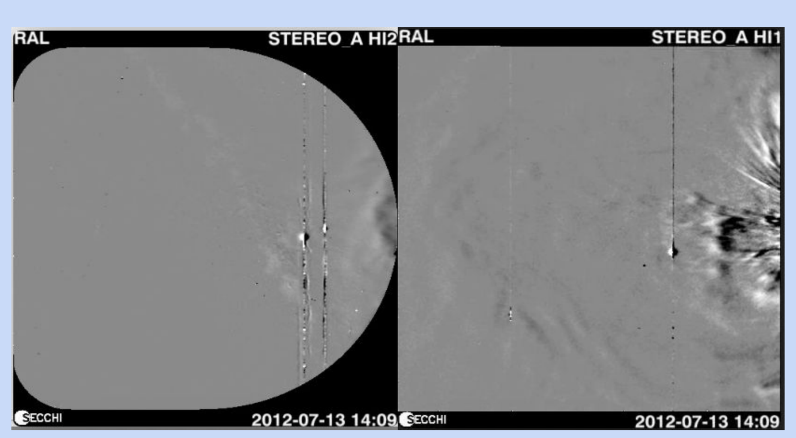
In this work, we constrain the kinematics of our MHD coronal mass ejection (CME) model with multiple viewpoints of STEREO coronagraph and heliospheric imager (HI) data to improve the arrival time predictions. We show our approach using the 12 July 2012 CME. Using the kinematics derived from coronagraph observations and using the graduated cylindrical shell (GCS) model, we simulated a flux-rope-based CME. By comparing simulations and observations of this event at Earth, we found that our simulated CME arrived ~2.5 hours after the observed CME. To compare the evolution of our simulated CME with observations in the inner heliosphere, we created synthetic J-maps from our simulation data and compared them with the J-maps created from STEREO HI observations. By comparing the time-elongation angle graphs extracted from the synthetic and observed J-maps, we found that on average our simulated CME was trailing the observed CME by 2 hours in both STEREO A and B. Offsetting this time from the arrival time of our simulated CME reduces the arrival time prediction error to just 0.5 hour. Therefore, constraining MHD models with HI observations has the potential to improve the arrival time predictions. This approach will be validated by performing simulations of multiple other CMEs as a future work.

Introduction

Predicting the arrival time of Coronal Mass Ejections is a monumental step in Space Weather Predictions. CMEs are large eruptions of plasma and magnetic field resulting from the active regions on the Sun's surface. Earth directed CMEs can cause extreme geomagnetic storms as a consequence of their interaction with Earth's magnetosphere.

Credit: European Space Agency (ESA)

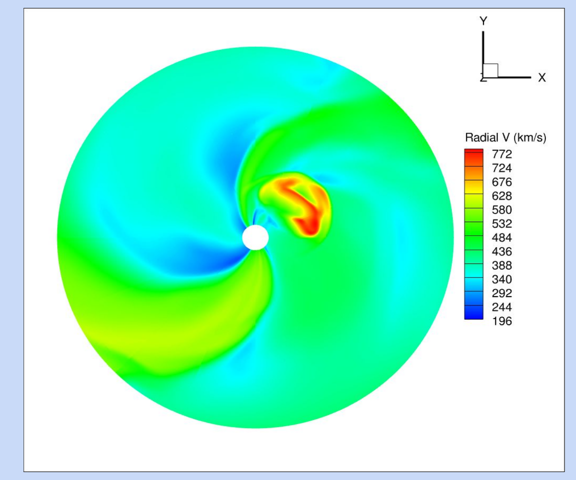
These storms can cause damage to satellites, which can result in loss of GPS signal. They can also disrupt electrical transmission lines, and pose threat to the crew and passengers on high altitude flights. It is imperative that we predict the arrival time of CMEs with high accuracy so we can take necessary actions to minimize their effects. "The bipartisan PROSWIFT (Promoting Research and Observations of Space Weather to Improve the Forecasting to Tomorrow) Act, passed into law in October 2020, is formalizing the need to develop better space weather forecasting tools."(Mike O'Neil, 2021))



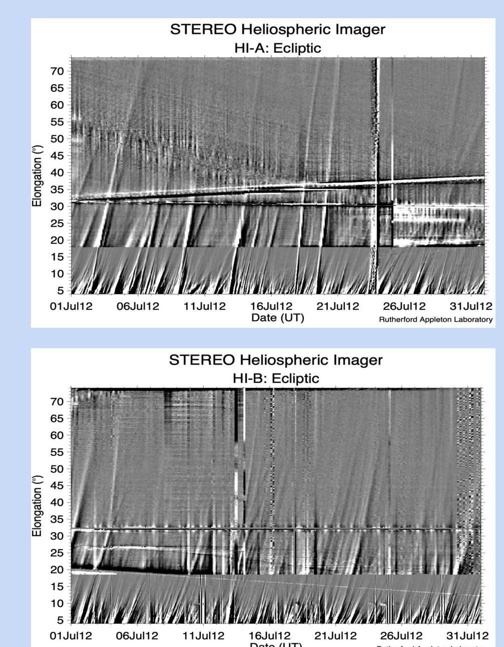
In this Research, we will be working with a simulation of the 12th July, 2012 CME. The picture on the left shows this observed CME from both Heliospheric Imager 1 (HI1) and 2 (HI2). The goal is to track the CME front and predict the arrival time in the simulation. Then compare the results to the actual arrival time as observed.

Methods

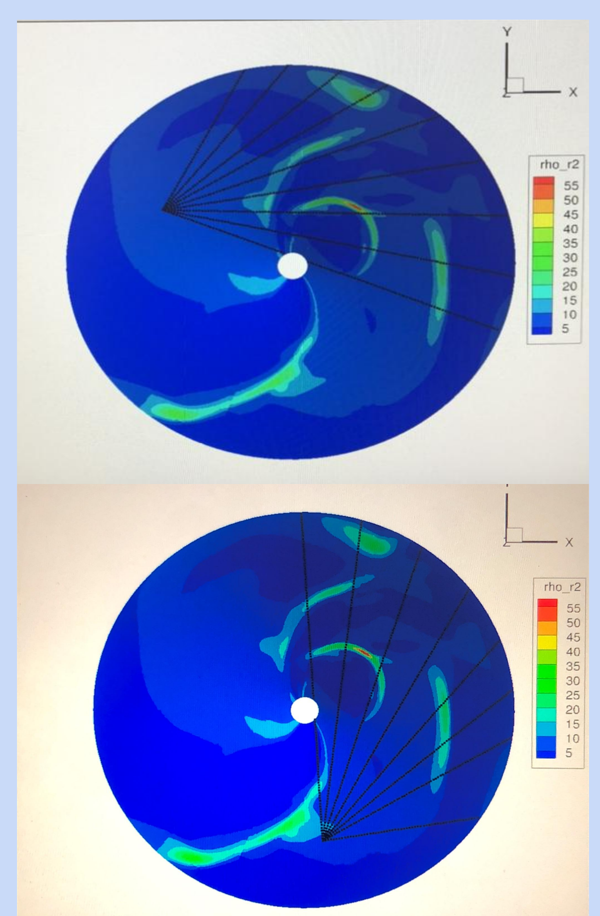
A simulation of the 12th July, 2012 CME was developed by our team. The outer boundary of our domain was 1.5 AU. The domain was divided into small cells and MHD equations were solved in these cells. The inner boundary used was 12 Solar radii, and we used Sun's magnetic field boundary conditions to start the movement of the CME. The figure on the right shows the propagation of simulated CME (Radial velocity) through our domain. The next objective in our work is to track the CME front through the field of view of HI2 on both STEREO A and STEREO B.



J-maps can be extremely helpful when calculating the time-elongation data of a CME. J-maps are basically made by taking slices of the ecliptic plane in time, which show the CME front moving through the interplanetary medium. We then put these slices in a vertical stack. We make the stack horizontal and plot. Physical time becomes the horizontal axis and the elongation angle of HI becomes the vertical axis. The diagrams on the right are the observed J-maps created from the field of view of HI aboard STEREO A and B respectively. Our goal is to make synthetic J-maps; the ones generated by looking at the density distribution as the simulated CME travels through the IP medium. Then we will extract time-elongation data from both observed and synthetic J-maps for comparison.



J-maps for STEREO A (top) and STEREO B (bottom)
Credit: Rutherford Appleton Laboratory

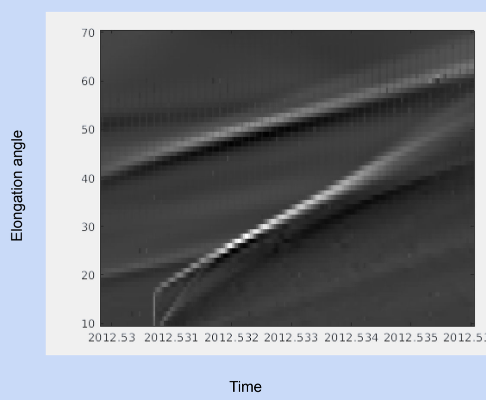


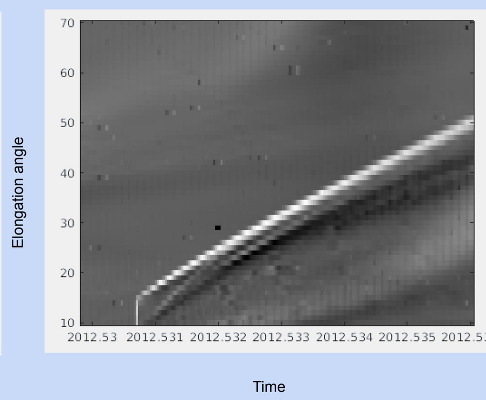
Field of view: STEREO A (top) and STEREO B (bottom)

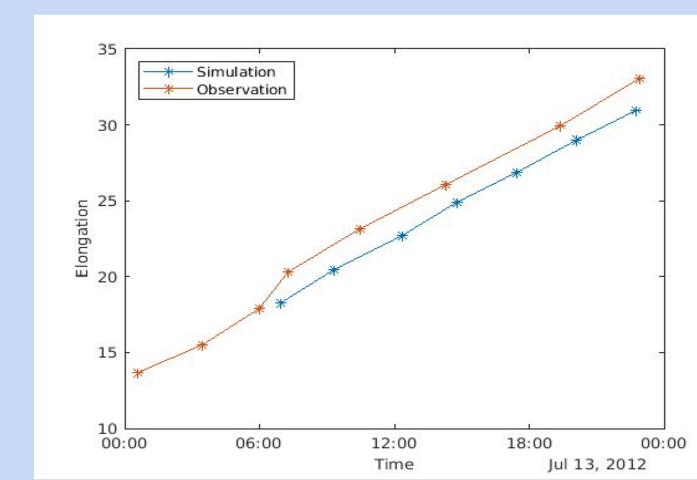
We located the STEREO field of view inside our domain using the trajectory data. The field of view was then integrated with respect to angle to create lines, and then integrated the lines into points. We know the density at all of these points on every line. We found the total density of each line by adding all the points on that particular line. Keeping in mind the circular nature of our domain, each line has different number of points. So we had to normalize our data by dividing the density sum of each line by the total number of points in it. We got a 2D density array for all the points. We plotted this array on a meshgrid with time and elongation angle on horizontal and vertical axis respectively. Lastly, we subtracted every column from the column ahead of it.This provides us with just the CME front. We use this method because we are only concerned with the arrival time of the CME to Earth (1 AU). The results are shown in the next section.

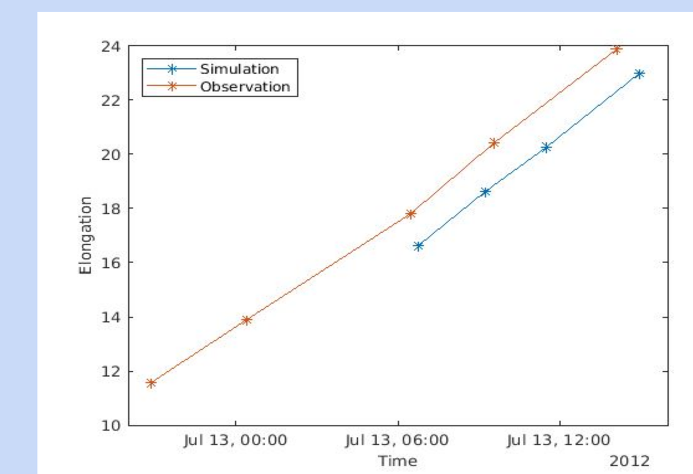
Results

The figures on the right are the synthetic J-maps constructed from the simulation data. The curves on the synthetic J-maps represent the CME front traveling through space. We then extracted the time elongation data from the J-maps by tracing the points on the curves. We also did the same for the observed J-maps and plot the results of simulation and observation below.









We got concrete data from STEREO A. Above plots mean that the observed CME gets to a given angle before the simulated CME. That means that our simulation is trailing behind the observed CME by ~2 hours. STEREO B's plot also agrees with this result.

Future Work

The next step is to use the computational approach in this study to analyze simulations of 6-7 more CMEs, and compare the arrival time with observations. We aim to publish our findings in a peer reviewed Journal.

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References

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