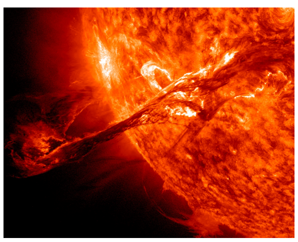
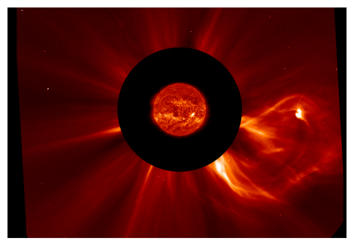
EUHFORIA: Modeling the dangers of the sun.

1 Introduction

When we look at the Sun in visible light, it looks rather boring. However, when we observe the Sun at other wavelengths, it gets very interesting! Various phenomena take place at the solar surface. We focus here on the phenomena that has the largest impact at Earth: **Coronal Mass Ejections (CMES)** (See Figure 1).



(a)



(b)

Figure 1: Figure (a) shows the Coronal Mass Ejection close to the sun during its eruption. Figure (b) shows the CME as it is propagating through the solar background wind. (Courtesy: ESA/NASA)

Coronal Mass Ejections are large eruptions that take place at the solar surface. A huge amount of plasma is emitted outwards at very high speeds. Sometimes, CMEs that are directed towards Earth can have an influence on our daily life e.g. aurora, problems with telecommunication systems or large power outages (See Figure 2). Scientists refer to the conditions on the sun and how they influence our conditions at Earth as **space weather**.

Observations of CMEs are limited (See Figure 1), and sometimes hard to interpret. It is hard to predict the arrival of a CME without using any kind of modeling or simulations. Therefore, space weather scientists have developed **mathematical models** to simulate how CMEs propagate towards Earth, so that we can have a better estimate on the arrival time and impact. We focus on the mathematical model called **EUHFORIA**, which has been developed at KU Leuven and University of Helsinki.

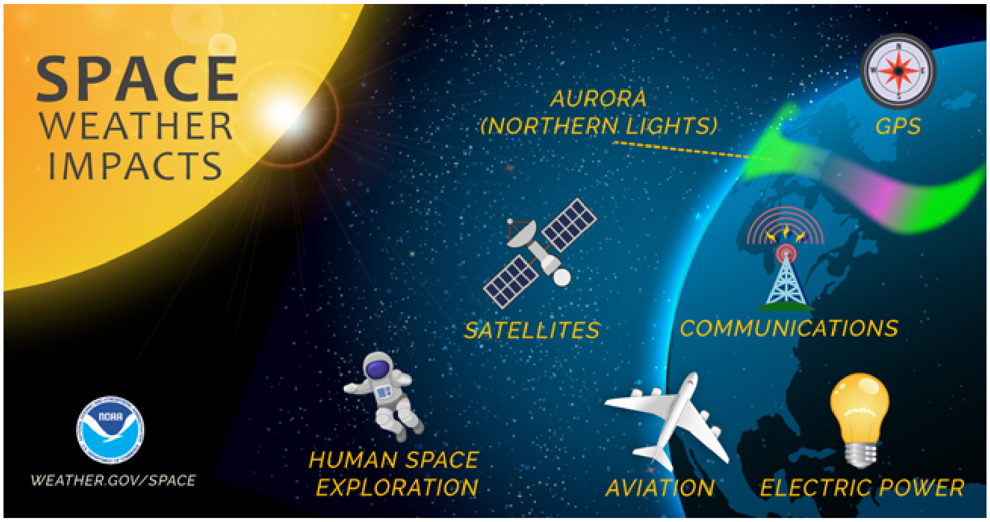


Figure 2: In this Figure we show the various impacts that space weather can have on our daily life. (Courtesy: NOAA/NASA)

2 Mathematics of the solar wind: EUHFORIA

Before we start with the mathematical models that simulate the CMEs, it is necessary to construct a **solar background wind**. The sun emits mass at a constant rate and because it is rotating, this results in a spiral like solar wind structure (See Figure 3). It is easy to compare this with spraying a water hose in circles. This will create the same spiral-like structure. The solar wind consists of different speeds and densities. The density and speed of the solar wind is influenced by phenomena that take place at the solar surface. Typical speeds are 250 km/s to 650 km/s.

To model this solar background wind mathematically, we are solving a set of equations called **MagnetoHydroDynamics (MHD)** (See Figure 5). The MHD equations solve a combination of fluid dynamics and Maxwells equations. The combination of these equations describes how a conductive fluid interacts with an ambient magnetic field. Solving the MHD equations, makes it possible to realistically simulate the solar wind from very close to the Sun up to the Earth and even beyond.

It is important that we include the **magnetic field** in the set of equations that we solve, as the solar wind as well as CMEs have a magnetic field, and its interaction with the magnetic field of the Earth is what is creating the so-called space weather.

After simulating the solar background wind, it is also possible to inject CMEs

$$
\begin{aligned}
\frac{\partial \rho}{\partial t} &= -\nabla \cdot (\rho \mathbf{v}) \\
\frac{\partial (\rho \mathbf{v})}{\partial t} &= -\nabla \cdot \left[\rho \mathbf{v}\mathbf{v} + \left(P + \frac{B^2}{2\mu_0}\right)\mathcal{I} - \frac{1}{\mu_0}\mathbf{B}\mathbf{B}\right] + \rho \mathbf{g} \\
\frac{\partial \mathbf{B}}{\partial t} &= \nabla \times (\mathbf{v} \times \mathbf{B}) \\
\frac{\partial E}{\partial t} &= -\nabla \cdot \left[\left(E + P - \frac{B^2}{2\mu_0}\right)\mathbf{v} + \frac{1}{\mu_0}\mathbf{B} \times (\mathbf{v} \times \mathbf{B})\right] + \rho \mathbf{v} \cdot \mathbf{g}
\end{aligned}
$$

Figure 3: In this Figure we show the MagnetoHydroDynamics set of equations that we are solving to simulate the solar background wind. These consist (from top to bottom) of the continuity equation, the mass conservation equation, Faraday's law and the energy conservation equation.

at the inner boundary of our model. This allows us to simulate how CMEs that are ejected from the Sun, propagate towards Earth.

3 CME representations

3.1 Coronal Mass Ejections

Before we talk about the different CME representations that our model can simulate, we should first learn about the structure of CMEs. When CMEs are observed before their eruption, we typically observe what scientists call a **twisted flux rope** (see Figure 4). A twisted flux rope consists of a plasma loop that contains a twisted magnetic field. A magnetic instability may trigger the eruption of the Coronal Mass Ejections and the mass that is trapped inside the twisted magnetic field structure is ejected outwards. Typical CME speeds range from 400 km/s to 1500 km/s. Hence, when a CME is ejected towards Earth, it typically arrives within about 3 days. The models that we use to simulate CMEs must therefore be able to solve the mathematical initial value problem within a day. This puts a limit on how we can simulate the propagation of CMEs.

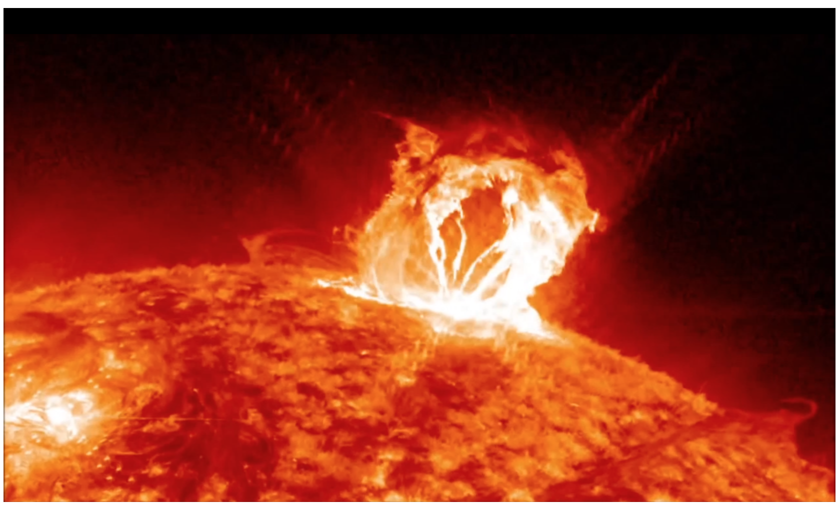


Figure 4: Typically, when CMEs are observed, we can see a twisted magnetic flux rope. (Courtesy: ESA/NASA)

Our CME models require information about the Coronal Mass Ejection that can be extracted from observations. The key parameters that we want to observe include the latitude and longitude at which the CME is ejected as well as the speed and width of the CME (see Figure 5).

3.2 The cone model

The **cone model** (see Figure 6) is a very simple model and it is the model that has been used extensively by space weather scientists for the past decade.

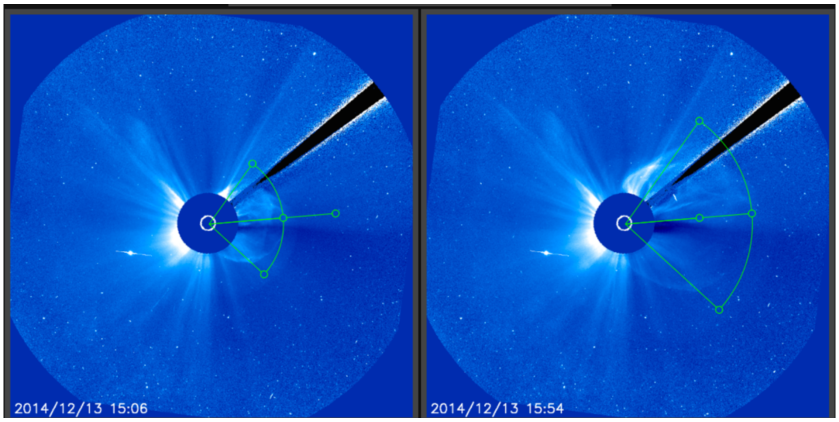


Figure 5: We can use a tool called StereoCAT, which allows us to estimate the width and speed of the CME as well as the longitude, latitude and time of ejection. (Courtesy: NASA)

The cone model simulates a CME as a sphere that is pushed through the inner boundary of EUHFORIA. It is modeled as a pressure and density enhancement. Notice that this model does not include an intrinsic magnetic field for the Coronal Mass Ejection.

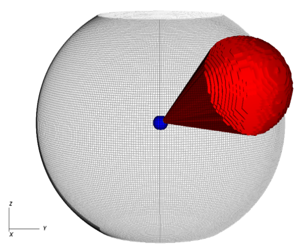


Figure 6: Overview of the cone model where a sphere is pushed through the inner boundary of EUHFORIA. Note that it is modeled as a pressure and density enhancement and therefore it does not include an intrinsic magnetic field.

3.3 The flux rope model

The flux rope model is mimicking the observed internal structure of the CME. It does include an intrinsic magnetic field. However, because we have a limit on our computation time, it is needed that we implement an analytic model that is fast to compute. In Figure 7, you can find an example of such a flux rope CME.

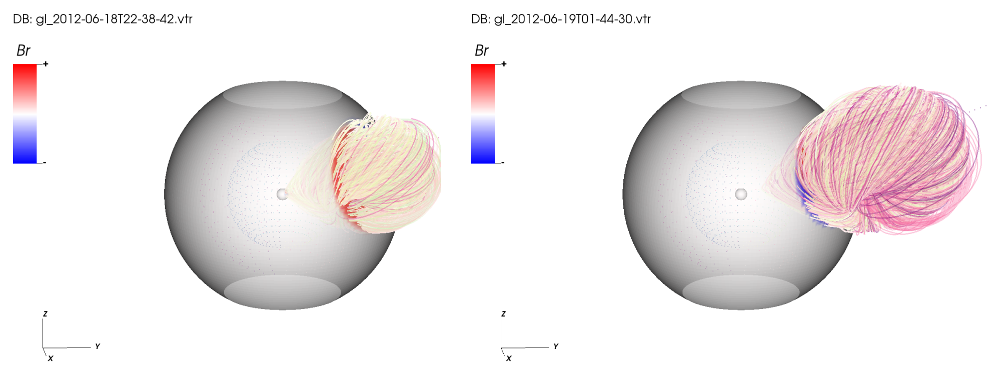


Figure 7: An example of a flux rope model that is being pushed through the inner boundary of EUHFORIA.

4 Results

4.1 Visualisation

In Figure 10, you can find an example of the typical visualisation that our space weather scientists use. The visualisation is shown so that we can have a maximum overview of what is happening at Earth and what is coming towards Earth: The ecliptic and the meridional plane in a color contour plot and a time series at Earth. In our coordinate system, Earth is always at the exact same spot: zero longitude.

4.2 Cone model

In Figure 9, we show a few snapshots of a series of CME events that have been modeled by EUHFORIA. We have modeled a total of 5 successive CMEs. In the time series (see Figure 10), you can see if the modeled CME arrives at Earth at the observed time or not.

4.3 Flux rope model

In Figure **??**, we show snapshots for the same event as for the Cone model. We have replaced one cone model CME with a flux rope mode CME. You can see that the overall structure of the CME is different and that it interacts with the solar wind in a different way than the cone model.

4.4 Comparison

As mentioned before, the magnetic field is an important parameter when it comes to determining the impact of the solar background wind and the CMEs at Earth, because of its interaction with the magnetic field of the Earth. Here

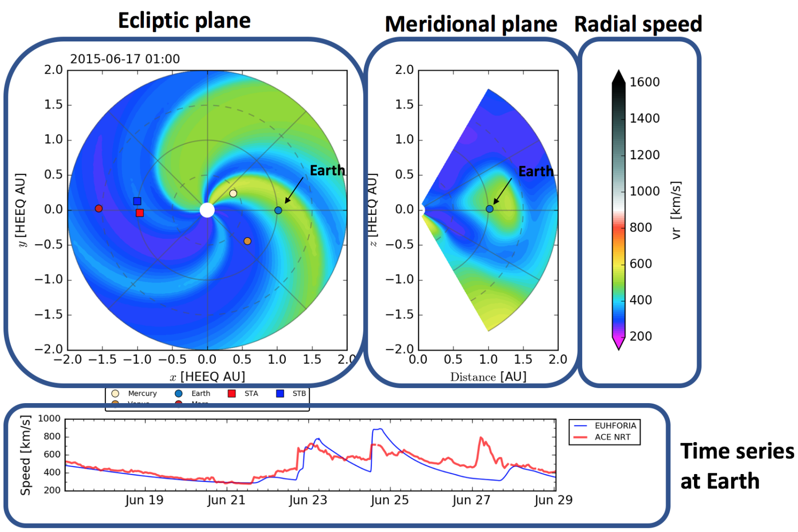


Figure 8: Overview of the typical visualisation used by space weather scientists. On the top panel we have the ecliptic and meridional plane where we plot the radial speed in a color contour plot. We also show the time series at Earth in the bottom panel. In red, observations by the ACE space craft are shown. In blue, the simulation models of EUHFORIA can be found.

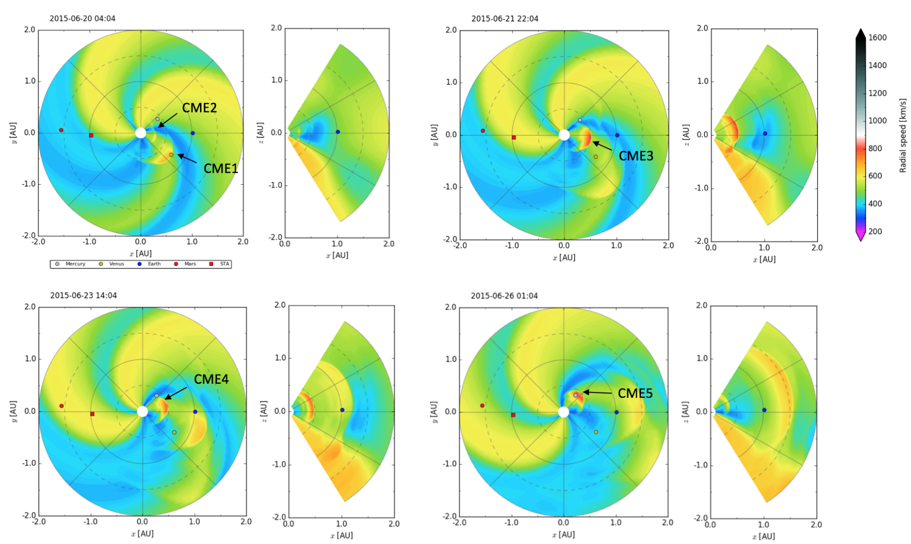


Figure 9: Snapshots of a model run where 5 succesive cone CMEs are being modeled.

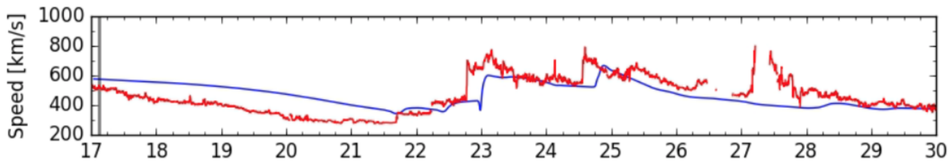


Figure 10: Time series of the radial speed at Earth for the same run as shown in Figure 9.

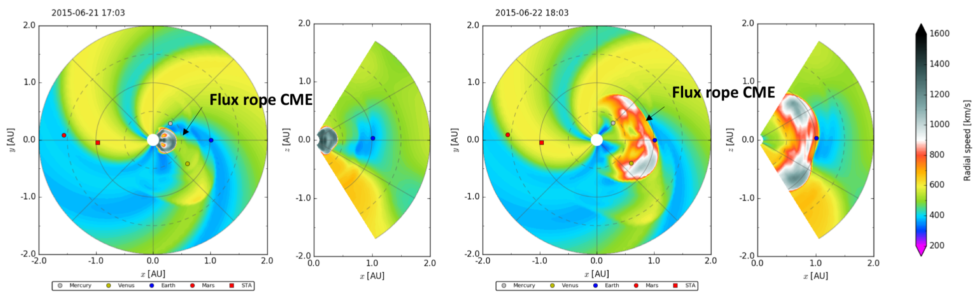
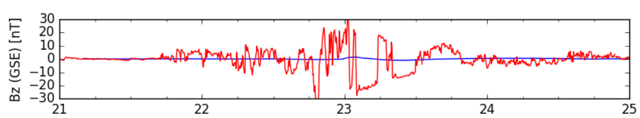
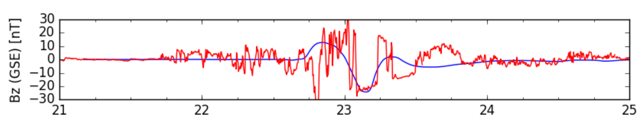


Figure 11: Snapshots for the same model simulation as in Figure 9. We have replaced one cone model CME with a flux rope CME.

we compare time series for both the simulation of the cone model as well as for the simulation of the flux rope model (see Figure 13). We can see that the cone model is not predicting any magnetic field disturbance at all. However, the flux rope model is able to capture much more of the physics that is observed.



(a)



(b)

Figure 12: Time series of the magnetic Bz component at Earth. We can see that the cone model (a) is not able to predict any magnetic field component, while the flux rope model (b) is able to capture the structure of the CME that is passing Earth.

5 Conclusions

The Earth's magnetic field is protecting us from the dangers from outside. However, once in a while, it is possible that a Coronal Mass Ejection launched from our Sun, has a large impact at Earth. Our model EUHFORIA helps with predicting the arrival times and impacts of such CMEs, so that we can prepare ourselves at Earth when a large CME is coming our way

Want to know more? Questions?

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