Towards a Data-Optimized Coronal Magnetic Field Model (DOC-FM): Simulating Flux Ropes with the Flux Rope Insertion Method

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Knowledge of the 3D magnetic filed structure at the time of major solar eruptions is vital or understanding of the space weather effects of these eruptions. Multiple data-constrained techniques that reconstruct the 3D coronal field based on photospheric magnetograms have been used to achieve this goal. In particular, we have used the flux rope insertion method to obtain the coronal magnetic field of multiple regions containing flux ropes or sheared arcades based on line-of-sight magnetograms and X-ray and EUV observations of coronal loops. For the purpose of developing statistical measures of the goodness of fit of these models to the observations, here we present our modeling of flux ropes based on synthetic magnetograms obtained from Fan & Gibson emerging flux rope simulation. The goal is to reproduce the flux rope structure from a given time step of the MHD simulations based only on the photospheric magnetogram and synthetic forward modeled coronal emission obtained from the same step of the MHD simulation. For this purpose we create a large grid of models with the flux rope insertion method with different combinations of axial and poloidal flux, which give us different morphology of the flux rope. Then we compare the synthetic coronal emission with the shape of the current distribution and field lines from the models to come up with a best fit. This fit is then tested using the statistical methods developed by our team.

Introduction

Most flare and CMEs originate in active regions that host a coronal flux rope before or during the eruption. One of the first goals of the DOC-FM project on the road to better predicting coronal magnetism is finding ways to fit simulated observations from the forward-fitting code, FORWARD, and realistic 3D coronal models. Ideally, we would like to fit coronal magnetometry observations from COMP with 3D magnetic field obtained from the flux rope insertion method for producing non-linear force-free fields (NLFFF). But, before that, we need a controlled case where we know the 3D coronal input that creates the FORWARD observations and we model this input. So, the purpose of these initial steps is to take a flux rope from Fan & Gibson (2003) simulation of an emerging flux rope some time after the whole axis of the flux rope has emerged and model the MHD simulation output at this step with a NLFFF mode. After this has been accomplished a new method for sampling the parameter space of models to be fit will be applied (Dalmasse et al. 2016) and the best-fit solution to the FORWARD observations will be found.

The Flux Rope Insertion Method

• van Ballegooijen (2004) – the Coronal Modeling System (CMS)

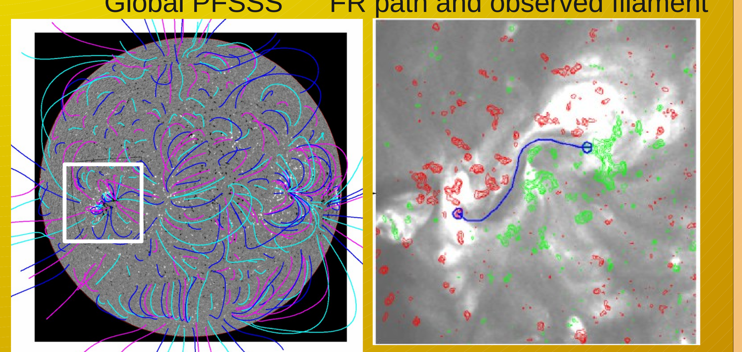
- Global + partial hires potential field extrapolations from LoS MDI/HMI magnetogram
- Insert flux rope along a filament (STEREO, AIA 304A, Hα)
- Relax using magnetofriction (MF). MF iterates the induction equation in terms of the vector potential, A, until the MF velocity vanishes for a NLFFF model

$$\frac{\partial \mathbf{B}}{\partial t} = \nabla \times \left(v \times \mathbf{B} - \eta_i \nabla \times \mathbf{B} + \frac{\mathbf{B}}{B^2} \nabla \cdot (\eta_4 B^2 \nabla \alpha) \right)$$

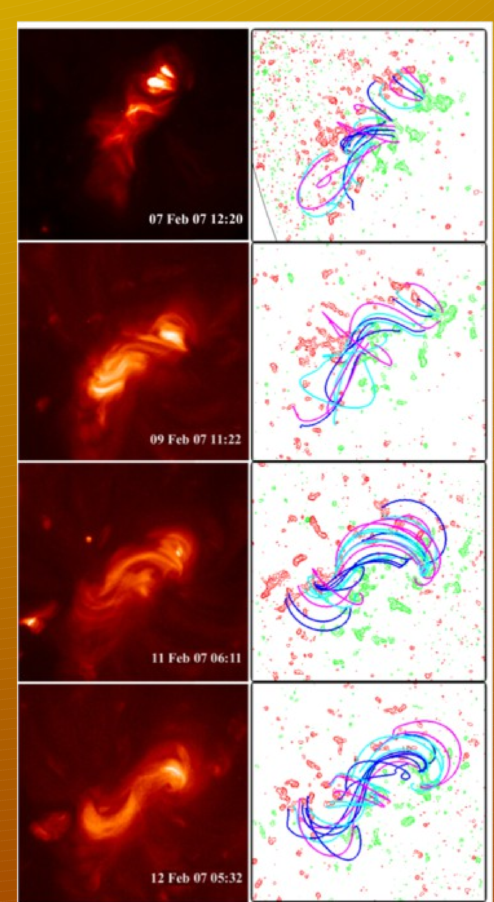
$$v = (f\mathbf{j} - v_1 \hat{\mathbf{r}} \times \mathbf{B}) \times \frac{\mathbf{B}}{B^2},$$

- For an unstable model V is non-zero
- Create a grid of models with different combinations of axial and poloidal flux
- Fit field lines from models to coronal loops and select best-fit model

Global PFSS   FR path and observed filament



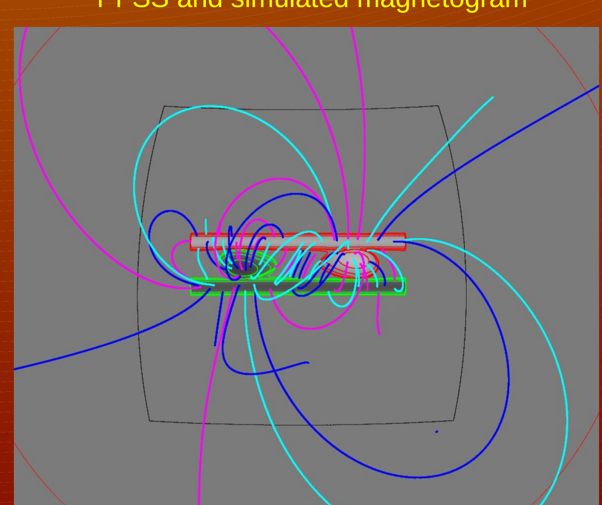
XRT data   Field lines from the best-fit model



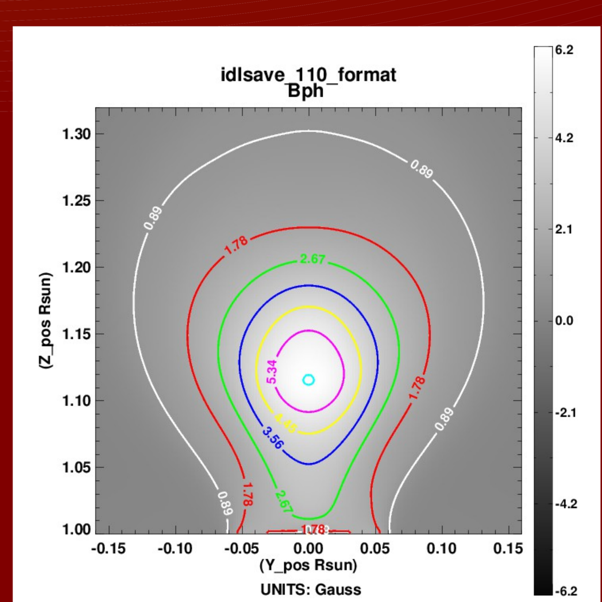
Fan & Gibson Flux rope and Modification to the FR Insertion Method

• Take one time step from Fan's simulation
• Export bottom boundary condition as a simulated photospheric magnetogram
• Use as bottom B.C to CMS
• No global magnetogram, so leave sides and top open
• Perform potential field extrapolation
• Insert flux ropes with different combinations of axial (up to 30% of magnetogram flux (10^{22} Mx)) and poloidal flux (from -10^9 to -10^{11} Mx/cm)
• The paths of the flux ropes are set by a simulated observation from FORWARD in AIA 193
• The 3D structure of the rope can be fit to the 3D structure of the FG flux rope (what we do here) or the FORWARD out of the two magnetic confugurations can be fit (next step)

PFSS and simulated magnetogram



Poloidal field of MHD flux rope in cross section



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Van Ballegooijen, 2004, ApJ, 612, 519
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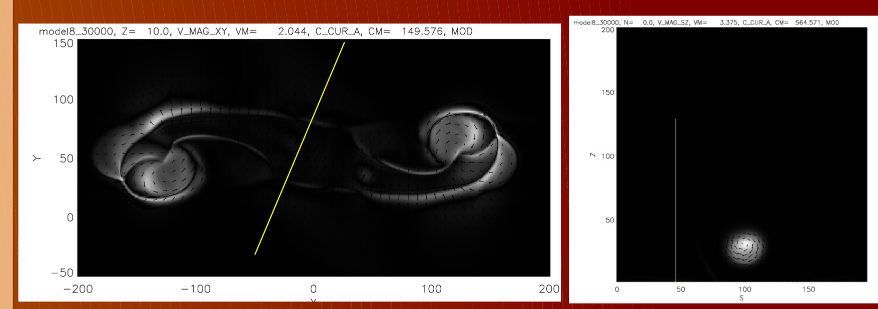
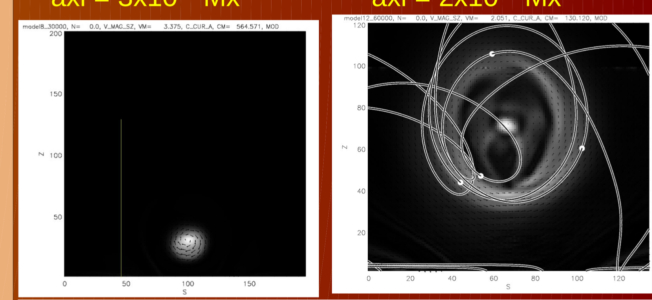
Effect of Axial and Poloidal Flux on the Flux Rope Current Distribution

1. Low axial flux creates thin flux ropes at small heights, need larger axial flux
Pol. Flux =-1×10^{10} Mx/cm, Axial flux = 3×10^{19} Mx

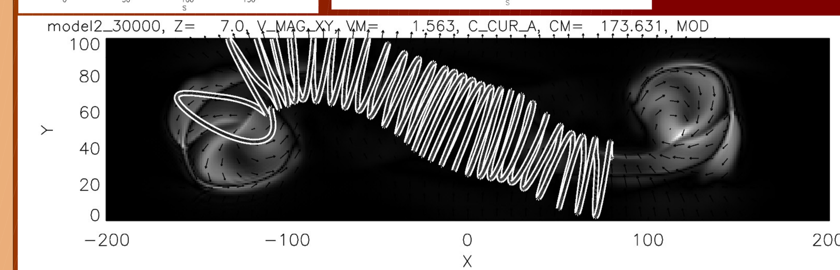


pol=-1×10^{10} Mx/cm, axi = 3×10^{19} Mx   pol=-1×10^{10} Mx/cm axi = 2×10^{20} Mx

2. Effect of increasing axial flux, hollow core cross-section, flux rope more elevated

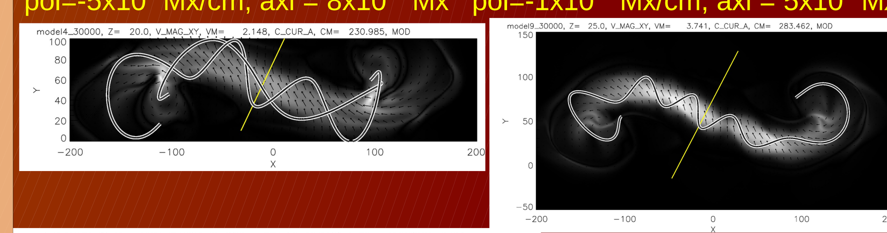


3. Poloidal flux > -10^9 Mx/cm creates too twisted flux ropes. Pol= -5×10^9 Mx/cm, Axi = 3×10^{19} Mx

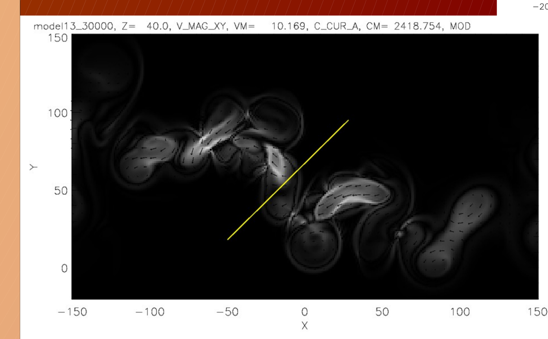


pol=-5×10^9 Mx/cm, axi = 8×10^{19} Mx   pol=-1×10^{10} Mx/cm, axi = 5×10^{19}Mx

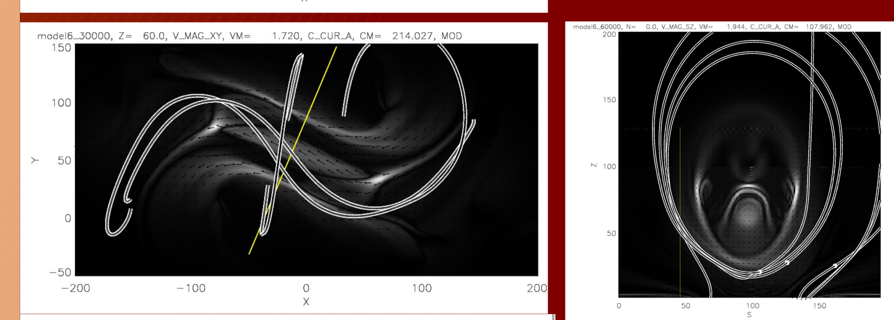
3. Increasing the axial flux reduces the twist and the flux rope elevates.



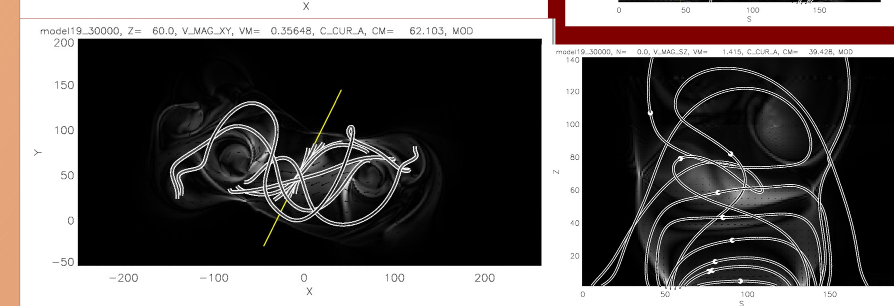
4. In some cases, a kinking flux rope, when high poloidal and low axial flux.
pol=-5×10^{10} Mx/cm, axi = 1×10^{19} Mx



5. High axial flux: core substructure, flux rope expands. pol=-5×10^9 Mx/cm, axi = 2×10^{20} Mx

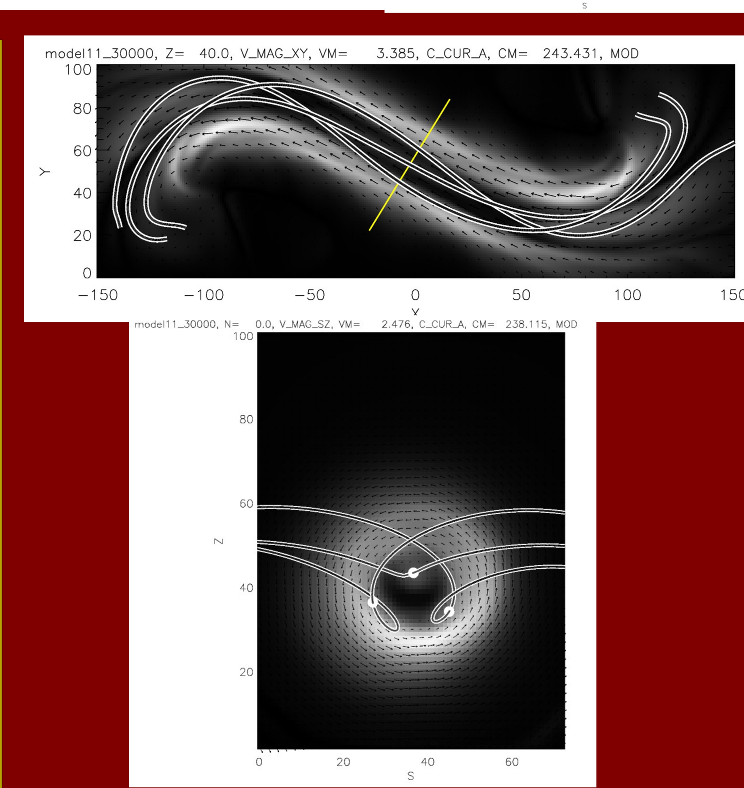


6. Wrong sign of poloidal flux: reconnection above the flux rope. pol=5×10^9 M/cm, axi = 3×10^{19} Mx



The Best-fit Model

• Su et al. (2011) and Savcheva et al. (2012, 2015) determined that rising axial flux makes the flux rope expand and elevate, and ultimately makes it more unstable.
• In the cases of marginally stable or unstable flux ropes: change in the morphology and cross-section size and shape change with iteration number of the MF process
• So, need to fit the cross-section size, shape, height of the axis, and find which iteration of which model gives the best result.
• This is model: Pol. =-1×10^{10} M/cm, Axial = 1×10^{20} Mx



Conclusions and Next Steps

▪ The method for selecting the best-fit 3D magnetic field model from CMS to the actual FG flux rope will be explained in Dalmasse et al. (2016) and is covered in poster #
▪ We need to construct a reasonable parameter space of variables to be fit to the simulated observations. These will be: axial and poloidal flux, and iteration number of the MF relaxation (height of flux rope axis).
▪ In order to find the real boundaries of the flux rope we can use quasi-separatrix layers (QSLs) in cross-section as done in Savcheva et al. (2012). The flux rope axis can be found with the method of Tassev & Savcheva (2016).
▪ A primer of the effect of polidal and axial flux on the flux rope features, shape, and size in cross-section as well as in horizontal view through the axis will be presented in Savcheva et al. (2016).
▪ A suit of actual flux rope models will be made exploring the parameter space of polar crown filaments, so that a match between these models and coronal polarimetry observations from COMP can me made.