DIMMINGS AS A MAGNETIC FOOTPRINT OF CORONAL MASS EJECTIONS

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ABSTRACT

Large regions of coronal dimming often accompany coronal mass ejections (CMEs). Of all of the EUV signatures of CMEs, dimmings (when present) are the best match to the location and extent of the coronagraph CME observations. They last on timescales from minutes to hours, are sometimes patchy in appearance, and can extend far (>1 RSun) from the flaring region. They are known to be good indicators of the site of evacuated material, and have been extensively studied as a CME mass source.

We investigate the possibility that dimmings also serve as a magnetic footprint of CMEs. Dimmings develop during or soon after the eruption, and may trace field lines locally opened during the CME. These dimming regions can be extensive, representing at least part of the "base" of a CME and the mass and magnetic flux transported outward by it. We report on three-dimensional observations of the co-development of dimmings in EUV and coronagraph images, magnetic field topologies represented by the dimmings, and in situ observations that can be used as a diagnostic of the erupting field topology.

EUV CORONAL DIMMINGS

"Coronal dimmings," i.e. dark regions on the Sun that accompany an eruption, have been shown to be an effective indicator of evacuated material in the low corona. They can extend over a large fraction of the solar disk and exhibit a variety of topologies.

However, dimming regions can evolve over many hours, and one part of the dimming can completely "refill" before another part appears. Additionally, bright flare loops can obscure part of the dimmings.

Figure 1: SDO AIA combined wavelength images for the dimming/flare/CME event on 2010 November 30. Regions A - E all exhibited dimming at some point during the event, but the much of the early dimming has disappeared by the time region 'E' appears.

Figure 2: "Persistence maps" (Thompson & Young, 2016) were constructed for the regions using the minimum criterion: throughout the time window, the minimum value per pixel was retained in the map. Persistence eliminates the flaring region completely, solving the obscuration problem. The full extent of the dimming regions are identified over the course of 8 hours.

Figure 3: The final Persistence Map is shown in the lower panel, with color outlines corresponding to Regions A - E indicated above. The line plot above the figure compares the values derived from pre-event "base" image subtraction vs. that of the persistence method. The solid black line shows the percentage decrease in integrated emission of the combined areas marked A, B, C, D, and E, normalized to the pre-event value. The dashed black line shows value of emission decrease from the same combined regions as determined by the persistence method.

The subtraction vs. persistence values for each of the individual regions A - E are shown using their associated color (A = red, B = blue, etc.). The position of the region's values on the time axis indicates where the integrated emission in the region reached its minimum value. The pie chart superposed on the figure shows the relative contributions of the regions A - E to the total measured dimming.

The largest dimming region, C, reaches its minimum value almost two hours after Regions A and B. By this time, the flare loops have already begun to obscure Regions A & B. This can result in a gross underestimate of the total mass loss (45% vs. 65%).

Fig 1. "Normal" 3-color images 211Å = red, 193Å=green, 171Å=blue

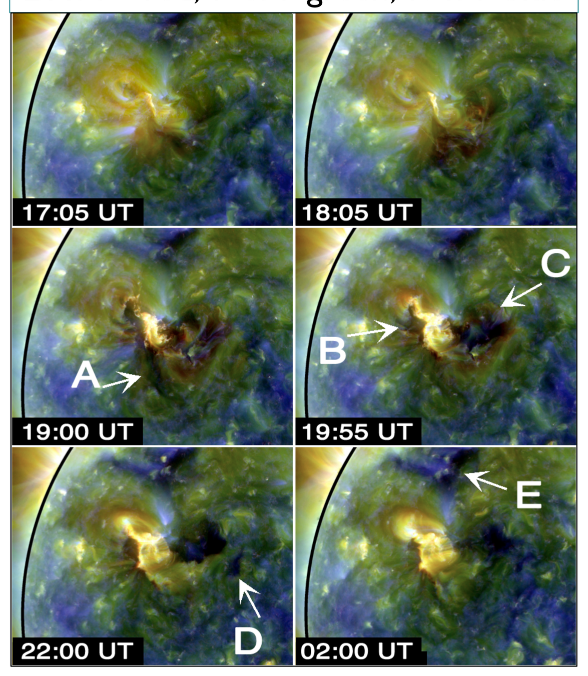


Fig 2. Persistence map, % change (quadratically weighted)

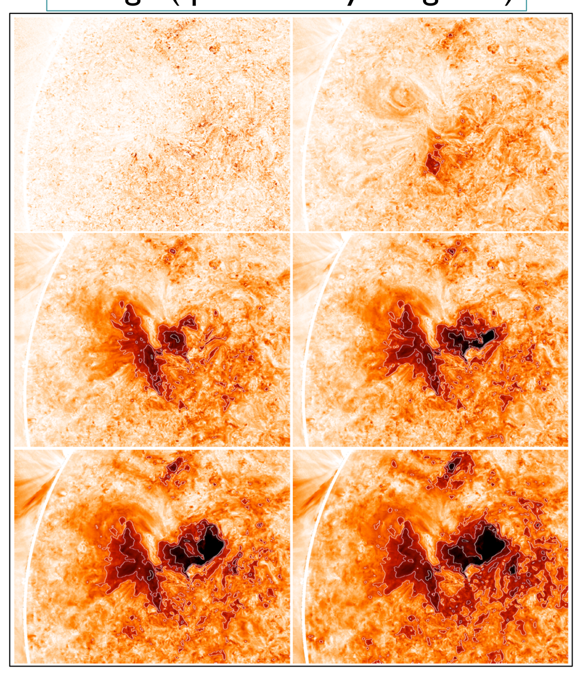
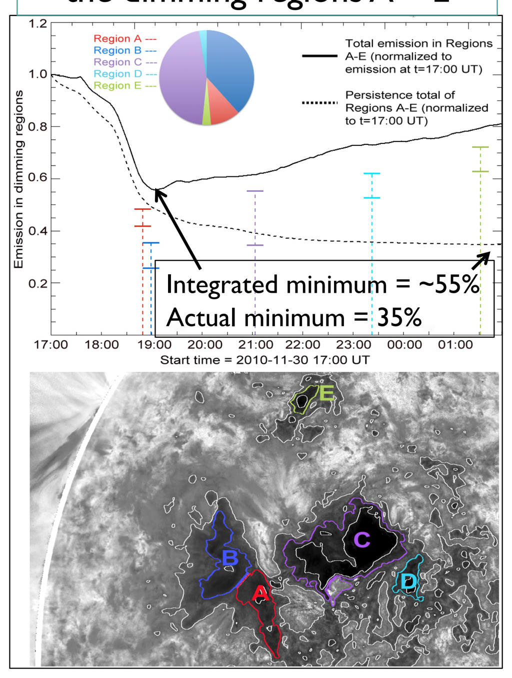
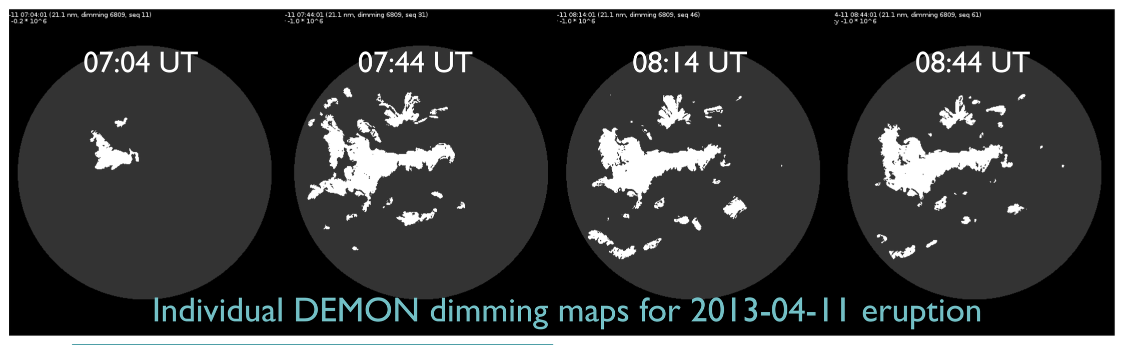


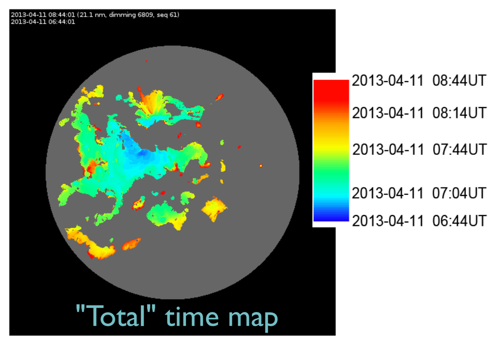
Fig 3. Temporal evolution of the dimming regions A – E



DIMMING & B FIELD MAPPING

Persistence maps were constructed using the Solar DEMON automated dimming detection algorithm (Kraaikamp & Verbeeck, 2015). DEMON identifies dimmings in SDO AIA 211 Å images as they evolve in time. >4500 "total" DEMON dimming maps were created, color-coded according to the time that each pixel first recorded a dimming.





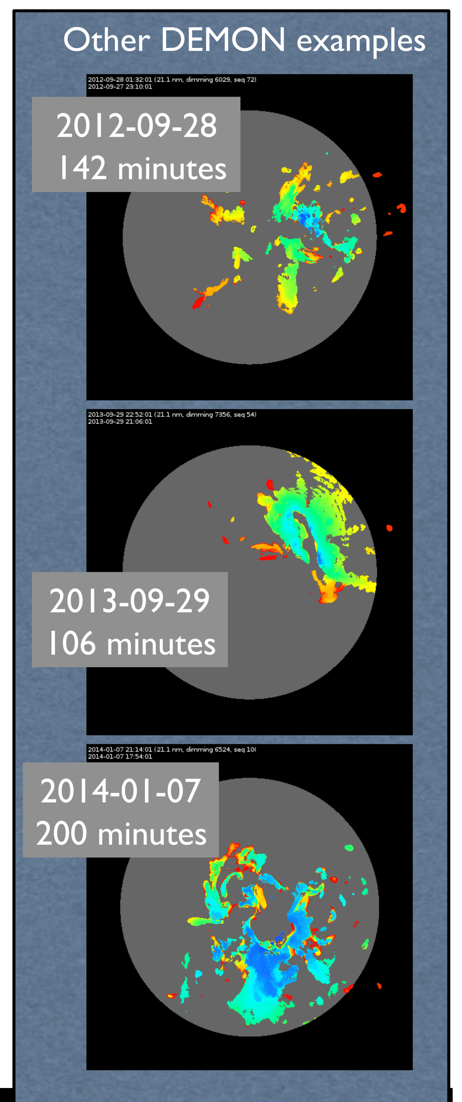
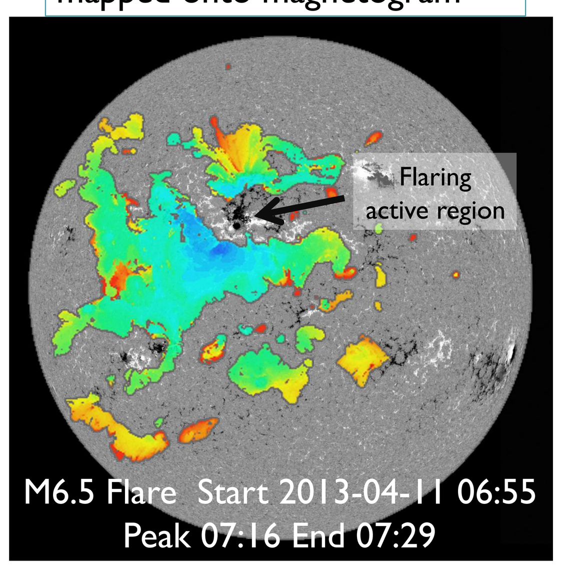


Fig 4. 2013-04-11 dimming mapped onto magnetogram

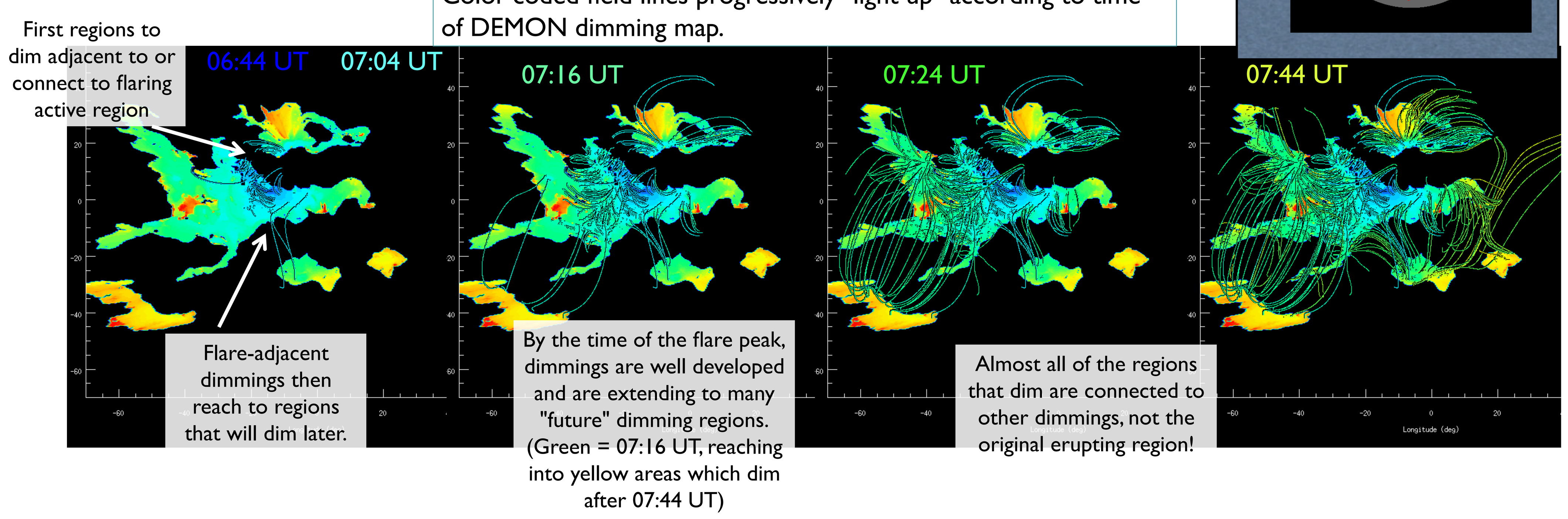


For the 2013-04-11 CME, most of the dimming area formed over the course of the first hour (06:44-07:44 UT). The first regions to dim were adjacent to the flaring active region (Figure 4).

A nonlinear force-free (NLFF) extrapolation of SDO HMI vector magnetic fields was performed (Tadesse et al., 2009, 2013), and field lines that map into the dimming regions were examined as a function of dimming time.

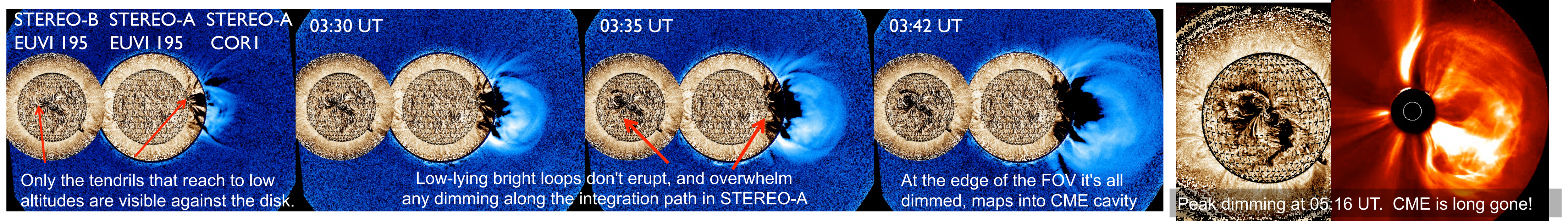
Note: this is a single extrapolation from around the time of the eruption. The time progression shows the field lines extending from areas that dim, color-coded according to their dimming time. The NLFF extrapolation does not in itself imply an eruption. As the dimmings are primarily in quiet sun regions, we do not expect the field to change significantly during eruption.

Fig 5. NLFF extrapolation of dimming magnetic fields in Figure 4. Color-coded field lines progressively "light up" according to time of DEMON dimming map.

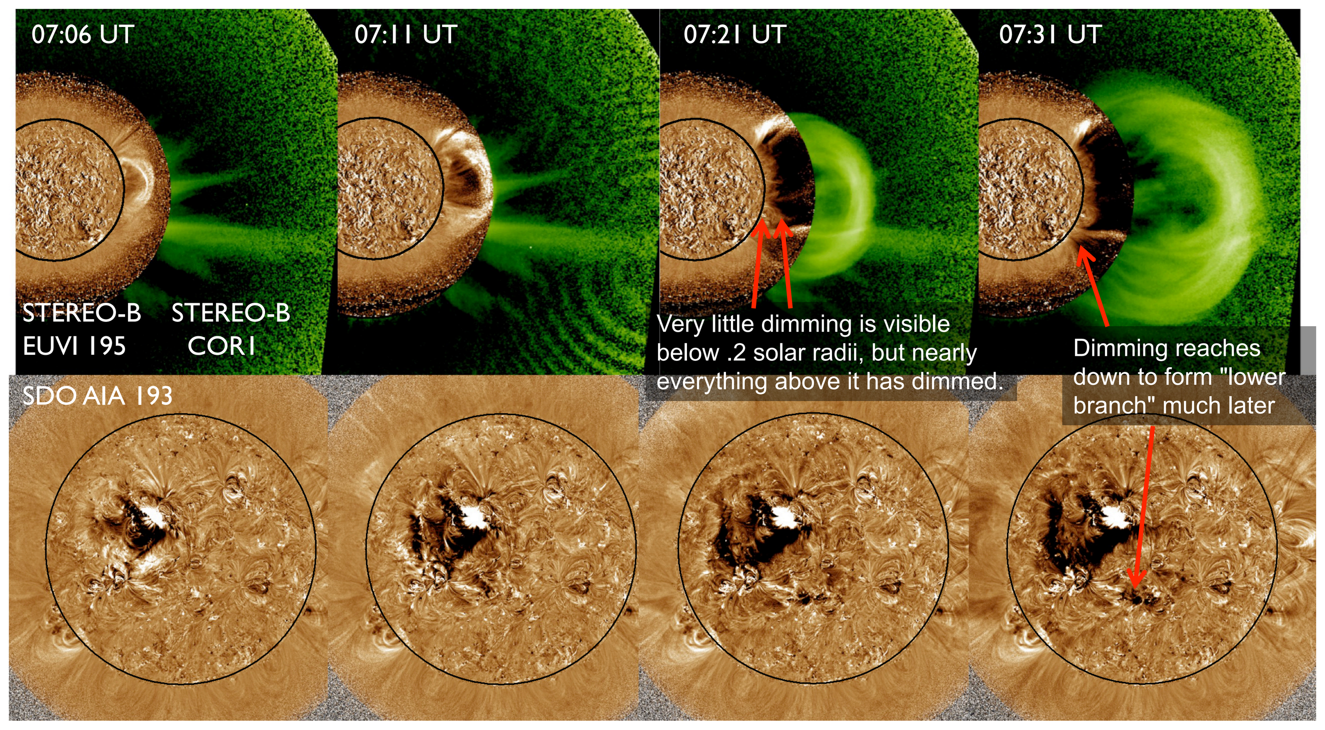


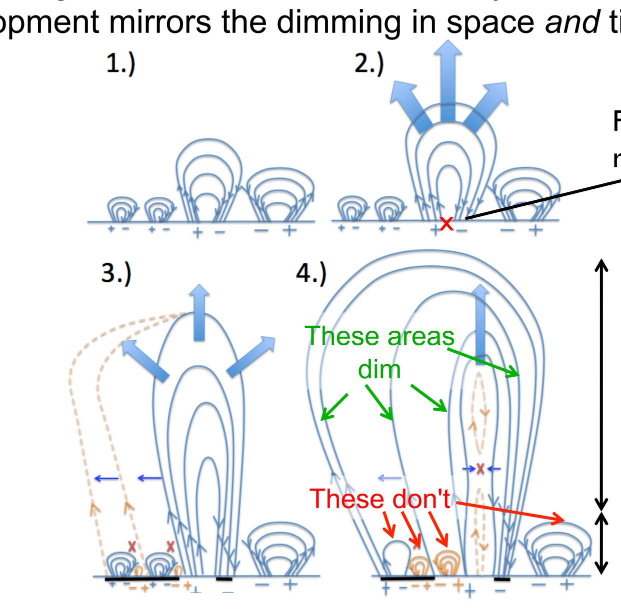
CME MAPS

2013-03-05 Dimming/CME: On-disk dimming observed by STEREO-B EUVI seems to have unusual structure. However, when viewed from the side with STEREO-A, the dimming appears to be a continuous structure high in the corona, reaching into the lower corona only in certain locations. Integration path can greatly influence the appearance of a dimming! However, most observations seem to indicate that above a certain altitude, everything is part of the eruption, and the dimming maps clearly into the CME cavity.



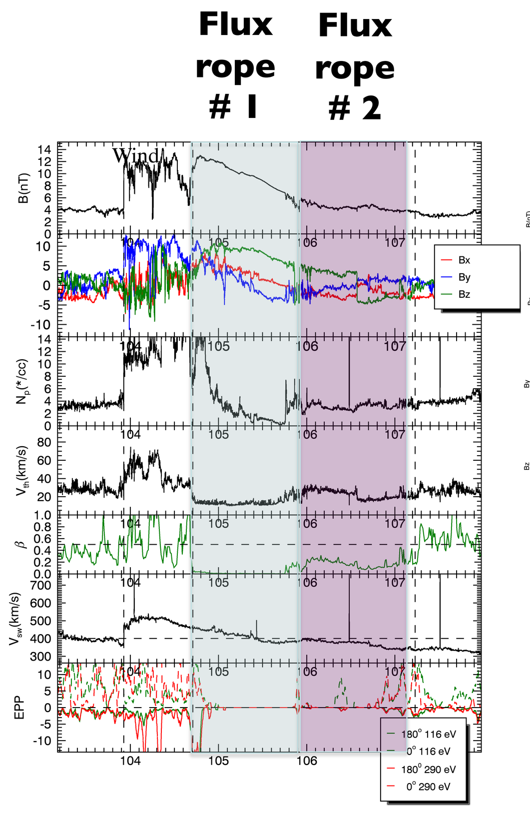
"Our" 2013-04-11 CME: a similar story. On disk, the dimming has a fairly intricate shape. Against the limb of the Sun, very little dimming is seen low-down. However, above ~.2 RSun the entire corona dims, and the CME cavity development mirrors the dimming in space *and* time.

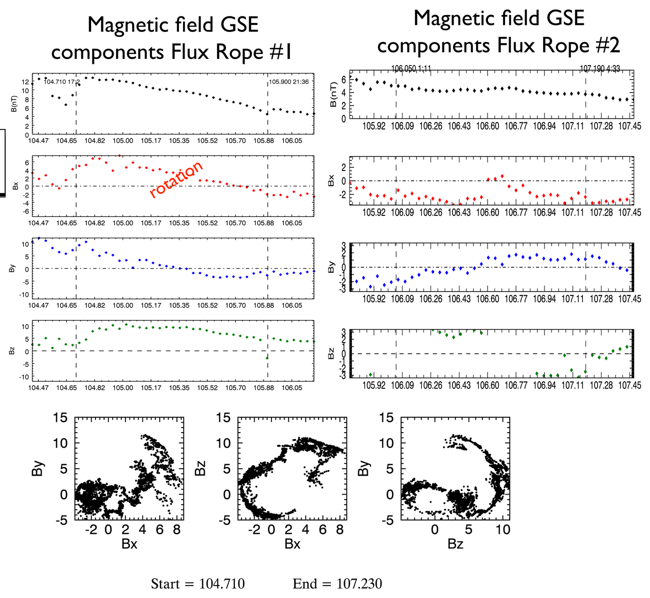




The dimmings fit the Krista & Reinard (2013) picture where a local eruption connects to other open fields via the large-scale corona, skipping over other low-lying structures that do not participate in the eruption.

IN SITU COMPARISON





Flux rope 1	Flux rope 2
<Vsw> = 412.5 km/s	<Vsw> = 366.7 km/s
Bmax = 12.7 nT	Bmax = 5.3 nT
<B> = 9.6 nT	<B> = 4.3 nT
Stronger	Weaker
Orientation	**Orientation**
Phi = 238. (180º= Sun-Earth line)	Phi = 157. (180º= Sun-Earth line)
Theta = 88. (tilt)	Theta = 3. (tilt)
Y0 = 0.054 AU	Y0 = 0.005 AU
R = 0.149 AU	R = 0.046 AU
Larger	Smaller
Impact par = 36% from axis	Impact par = 11% from axis
H = +	H = -
Right handed!	Left-handed!
Fluxes	**Fluxes**
Axial flux = 2.9 10^21 Mx	Axial flux = 0.08 10^21 Mx
Poloidal flux = 95.1 10^8 Mx/L	Poloidal flux = 12.8 10^8 Mx/L

Fig 6. Dimming field as seen from STEREO-B viewpoint

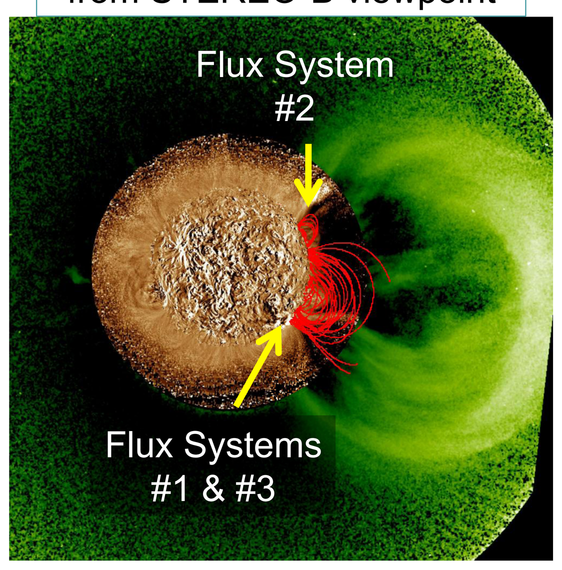
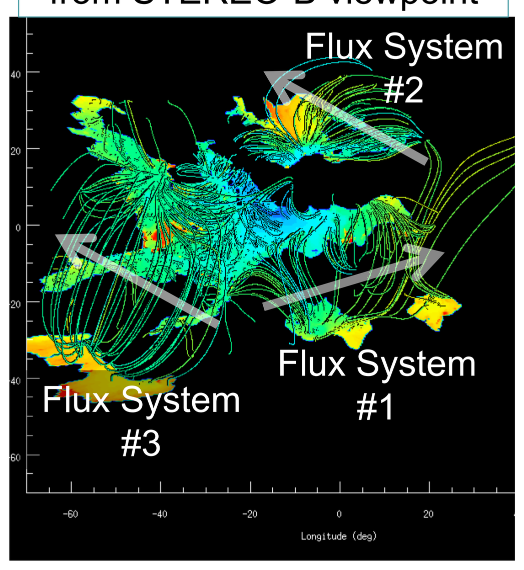


Fig 7. Dimming field as seen from STEREO-B viewpoint



The reprojection of the dimming fields to display them from the STEREO-B viewpoint, shown in Figure 6, shows that the dimming fields map very neatly into the CME cavity.

However, the Kay et al. FORECAT model predicts a deflection of the CME 13.6 degrees southward and 11 degrees eastward. If we make the assumption that the sub-regions of the erupting dimming hit Earth in the order predicted by the map, then Flux System #1 (labeled in Figures 6 and 7) will hit Earth first, Flux System #2 will hit second, and Flux System #3 will not hit earth at all.

The handedness and orientation of the flux systems are not inconsistent with the in situ measurement. However, much more needs to be done for this to function in a predictive capacity.

CONCLUSIONS

- **Asking *why* something erupted is not necessarily the same as asking *what* erupted.**
- Dimmings can have very different appearances depending on the angle of observation. Observed against the disk of the Sun, they can consist many unusually-shaped patches extending over a large distance. ***However, when observed in profile, dimmings are large connected regions that only partially extend to the lower corona. Above a certain altitude, "everything leaves."***
- Dimmings have been extensively studied as a mass source of coronal mass ejections. ***However, dimmings map into the interior/cavity of a CME, not the bright front.***
- The cavity of a CME corresponds, primarily, to the magnetic cloud observed in interplanetary space. Although local active region fields may be *responsible* for the eruption, they are only a small part of what fills the eruption. ***The magnetic field of a dimming corresponds to much of the magnetic field of a CME.***
- NLFF modeling of "patchy" on-disk dimmings reveal how they are connected in the large-scale corona, and can indicate what global fields participated in the eruption. ***Extrapolated magnetic fields match well with dimmings, and indicate the fields filling the interior of a CME.***
- *In situ* measurements indicate two separate flux systems impacted Earth. Initial comparisons between the dimming field and the *in situ* measurements show promise.