

Estimating changes in connection fluxes due to emergence or submergence

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Overview

The Minimum Current Corona (MCC) model provides a way to estimate stored coronal energy using the number of field lines connecting regions of positive and negative photospheric flux. This information is quantified by the net flux connecting pairs of opposing regions in a connectivity matrix. Changes in the coronal magnetic field, due processes such as magnetic reconnection, manifest themselves as changes in the connectivity matrix. However, the connectivity matrix will also change when sources emerge or submerge through the photosphere, as often happens in active regions. We have developed an algorithm to estimate the changes in flux due to emergence and submergence of magnetic flux sources. These estimated changes must be removed in order to quantify storage and release of magnetic energy in the corona.

The present work uses magnetograms from the Michelson Doppler Interferometer on the SOHO spacecraft, as in Figure 1. Lighter and darker pixels show vertical field, $B_z(x, y)$, out of and into the page respectively. For this particular magnetogram of AR 10273 (N06°, W32°), the verticle field varies from 2029G to -1642G.

Minimum Current Corona[2][5]

The MCC model is a self-consistent, analytic model of quasi-static 3-D field evolution, which relies on two assumptions:

1. Photospheric field is composed of discrete, unipolar regions surrounded by a contiguous region of zero vertical flux
2. Corona evolves quasi-statically through a series of flux-constrained equilibria (FCE), fields with the lowest magnetic energy that still match the photospheric boundary and contain the prescribed distribution of domain fluxes

The coronal field resulting from assumption 2 is current-free except along separatrices of the field. These ribbons of current store energy as stress in the internal field. The FCE fields have the same domains as a potential field, but with different domain fluxes. The FCE field is defined to minimize the magnetic energy, constraining each domain flux to remain constant under variation of the vector potential A .

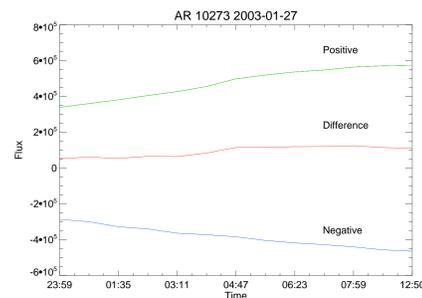


Figure 3: Flux (in Gauss) over time for AR 10273

Removing submerging/emerging flux

Figure 3 shows the positive, negative and total flux for AR 10273 over the course of one day. Note that there is a net amount of positive flux, both the positive and negative flux regions are emerging, and that the positive flux is emerging faster. In order to use the MCC model to estimate the amount of magnetic energy stored in coronal current ribbons, we need to remove the effects of submerging and emerging flux. To do so, we identify pairs of subregions (poles) that are submerging or emerging through the photosphere together by creating a connectivity matrix for flux change over time.

References

- [1] H.J. Hagenarr, C.J. Schrijver, and A.M. Title, ApJ **481** (1997), 988.
- [2] D.W. Longcope, SolPhys **169** (1996), 91.
- [3] D.W. Longcope, G. Barnes, and C. Beveridge, ApJ **693** (2009), 97.
- [4] D.W. Longcope and I. Klapper, ApJ **579** (2002), 468.
- [5] D.W. Longcope and T. Magara, ApJ **608** (2004), 1106.

Partitioning[1, 3]

Partitioning the magnetogram occurs in three steps, via the gradient-based tessellation scheme:

1. Convolve the verticle field, B_z , with the Green's function for a potential extrapolation up to a height h from an unbounded plane:

$$K_h(x, y) = \frac{h/2\pi}{(x^2 + y^2 + h^2)^{3/2}}$$
2. Assign a unique label for all local maxima and every pixel strictly downhill with respect to $|K_h * B_z|$ from each maxima
3. Eliminate internal boundaries in unipolar regions when the saddle point $|B_z| > \min(|B_{pk}|) - B_{sad}$, where B_{sad} is a threshold

Figure 1 shows an example magnetogram before and after Partitioning. Each region is then characterized by its net signed flux and centroid location

$$\Phi = \int_{\mathcal{R}} B_z(x, y) dx dy \quad \bar{\mathbf{x}} = \Phi^{-1} \int_{\mathcal{R}} \mathbf{x} B_z(x, y) dx dy$$

We call the centroids, together with their associated net flux, sources or poles. Figure 1 depicts AR 10273 before and after partitioning, with each region labeled by it's pole.

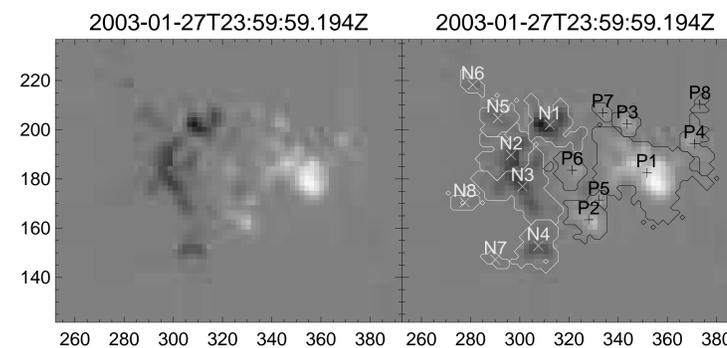


Figure 1: AR 10273 before and after partitioning. Distance measured in Mm from disc center.

The Algorithm

The change-in-connectivity matrix is not unique and will depend on the algorithm used to pair up submerging and emerging regions. Our algorithm avoids egregiously unphysical connections, such as those in Figure 5, where single poles have simultaneous submerging and emerging flux.

For a set of poles at two different times, $\{P_i^1\} \& \{P_i^2\}$, as in Figure 2, we do the following:

1. Create a symmetric change-in-connectivity-matrix, M_{ij}
2. Calculate the change in flux for each pole: $\Delta\phi_i = \phi_i^2 - \phi_i^1$
3. Find pole with smallest (but non-zero) changing flux, P_m , with flux change $\Delta\phi_m$
4. Find P_m 's nearest neighbor of opposite polarity and same sense in $\Delta\phi$, P_c
5. For P_m and P_c , cancel the minimum change in flux, $\min(|\Delta\phi_m|, |\Delta\phi_c|)$, from both $\Delta\phi_m$ and $\Delta\phi_c$, and encode that in the change-in-connectivity-matrix at M_{cm} and M_{mc}
6. Repeat steps 3-5 until no more submerging or emerging flux can be removed

An example run of this algorithm is depicted in Figure 4. The change-in-connectivity-matrix M represents an expected map of submerging and emerging flux between pairs of poles. This matrix of flux change can then be removed from the difference between the potential field's connectivity matrix at two times; for example, as in Figure 2. The remaining differences should then be due only to changes in the coronal magnetic field itself.

Figure 6 depicts the algorithm's output for the magnetograms in Figure 2. Because the algorithm operates on differences between sets of poles at different times, the same set of connections has been plotted at both timesteps.

Connectivity[4]

We define topologically distinct flux systems as *domains*, with each domain being the volume containing magnetic flux connecting only two photospheric sources. The amount of flux in a domain is the domain's *connectivity*. The MCC model fixes each domain's connectivity to a potential field's connectivity at some time. At a later time, the potential field's connectivity will have changed, whereas the connectivity of each domain has been kept constant. Figure 2 shows AR 10273's potential field's connectivity for two different times, 96 minutes apart.

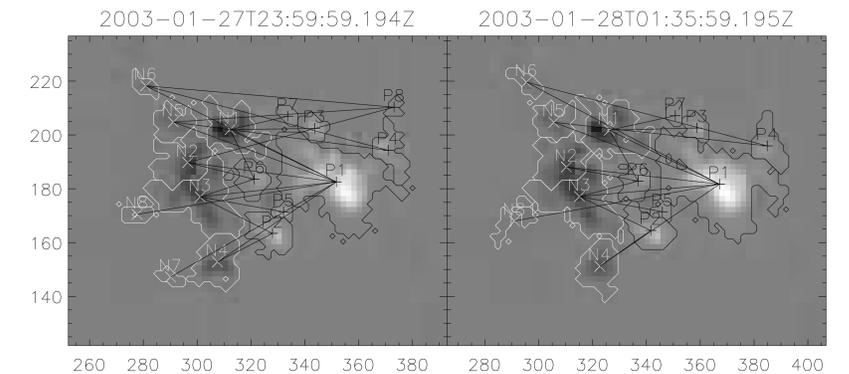


Figure 2: Potential field connectivity of AR 10273 at two different times

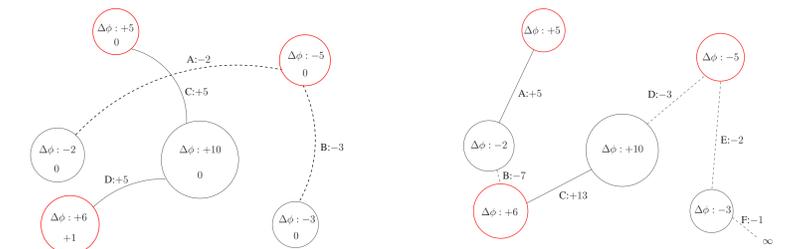


Figure 4: Example progression of the flux-change removal algorithm.

Figure 5: A different algorithm, connecting a region to the closet neighbor of opposite polarity.

In the above figures, red and black circles represent positive and negative flux regions, respectively. Inside each circle, the top number is the pre-algorithm change in flux relative to a previous timestep; when present, the bottom number is the flux change after submerging/emerging pairs have been identified. Lines between circles represent elements of the $\Delta\phi$ matrix, M , ordered (A,B,C...) by participation in the algorithm. Numbers on each line indicate the strength of the connection. This example has a net amount (+1) of emerging flux. A contrasting algorithm's connections are shown in Figure 5, in which each region connects to its closest neighbor of opposite polarity. This connection scheme produces unphysical simultaneous submergence and emergence in single poles.

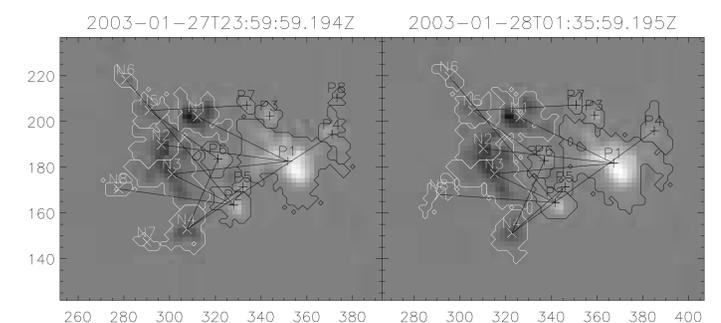


Figure 6: Representation of the change of connectivity matrix for AR 10273