NON LINEAR FORCE-FREE RECONSTRUCTION OF A FLARING ACTIVE REGION

A. Bleybel 1, T. Amari 2, L. van Driel-Gesztelyi 1, 3, and K. D. Leka 4

1 Observatoire de Paris, Laboratoire de Physique Solaire, DASOP, 91195 Meudon Principal, Cedex, France
2 (CNRS) DSM/DAPNIA Service d’Astrophysique, C-E Saclay, 91191 Gif sur Yvette Cedex, France
3 Konkoly Observatory, H-1525 Budapest. Pf. 67, Hungary
4 Colorado Research Associates, Boulder. CO 80301, USA

ABSTRACT

We present first results on the magnetic structure of active region NOAA 7912 involved in a long duration flare on 14 October 1995, and source region of a magnetic cloud observed by the WIND spacecraft between October 18-20. Using vector magnetograms from Hawaii Stokes Polarimeter (HSP) and Imaging Vector Magnetograph (IVM), and our recently developed code, we perform a reconstruction of the magnetic field above this active region, assuming it is in a non linear force-free state. This is used to determine some global properties of the active region magnetic field such as localization of electric currents, topology, magnetic energy as well as relative magnetic helicity. Comparison of some global quantities (energy & helicity) before and after the eruptive event is discussed.

Key words: Sun: magnetic fields - Sun: flares - MHD

1. INTRODUCTION

The evolution of magnetic field structure in the solar corona is responsible for most of the solar activity. The influence of the magnetic field extends also to the interplanetary space, and has important implications reaching the terrestrial magnetosphere. One of the important relations is the connection between eruptive flares and magnetic clouds, supported by many observational as well as theoretical evidences.

To prove this connection in a specific case, we reconstruct the coronal magnetic field in an active region before and after an eruptive event, using boundary values of the magnetic field in the photosphere, since the magnetic field is not directly observable in the corona. Non-linear force-free reconstructions are thus essential because of the large spectrum of length scales necessary for this kind of study.

Linear force-free reconstructions are useful but probably limited in this regard, as they require, in general, periodic boundary conditions over some length scale of the order of the dimensions of the active region, otherwise we are led to infinite total magnetic energy. Moreover, they limit the lengthscale of the electric current they imply to 1/α, where α is fixed to a constant value.

Potential model reconstruction is not adequate either, since it does not have free energy.

The paper is devoted to the reconstruction of the active region NOAA 7912 on 14 October 1995, and we show the connection of a long duration event (LDE) on this day with the magnetic cloud observed by WIND between 18-20 October, by performing a reconstruction of the magnetic field before and after the LDE and comparing parameters like total magnetic energy and relative helicity.

In section 2 we describe the active region AR7912, and its activity on 14 Oct 1995. In section 3 we perform data analysis. In section 4 we describe the method used for reconstruction. Section 5 is devoted to the results of the computation, and section 6 is a discussion. We give our conclusions in section 7.

2. THE ACTIVE REGION NOAA 7912

The region AR 7912 is a reversed polarity active region located in the southern hemisphere of the Sun. It consists of a negative polarity leading spot, and a more diffuse, globally positive polarity following
part. In NOAA 7912 an LDE started on 14 October at about 5 UT, reached maximum at 9:21 UT (SGD) and lasted for at least 15 hours (Figure 1). During the first four hours of the LDE, loops of sigmoid shape were seen to expand in the AR. Van Driel-Gesztelyi et al (1999) proposed that the magnetic cloud, which was observed by the WIND spacecraft at 1AU in the period of 18-20 October was ejected from AR during the LDE. A flux rope magnetic cloud model (Burlaga et al, 1981), was successfully applied to the WIND event (Lepping et al, 1997). The model and related analyses confirmed that the cloud had a dominant magnetic field which acted like a huge magnetosphere departing the Sun, stretched out in the ecliptic plane and had its own 'bow shock' ('driven' shock). The X-ray loops (see figure 3) have an S shape, with a positive helicity. This sigmoid shape is usually the signature of important helicity in solar active regions (Pevtsov et al, 1997).

![Image](image1.png)

Figure 1. Integrated soft X-ray emission between 12-16 Oct. 1995. Note the long duration event (LDE) on 14 Oct.

3. DATA ANALYSIS

We used photospheric vector magnetograms from the Imaging Vector Magnetograph (IVM, Mickey et al 1996; Labonte, Mickey and Leka 1999) to perform our calculations. The capabilities of the IVM encompass those of pre-existing magnetographs, with a time resolution of 10 minutes and an effective pixel size of 1.1 arcsec. There is one caution to take with this type of magnetograph: the IVM may make scale errors in the magnetic flux strength, but accurately represents the spatial structure. This is in contrast to spectrometer-based designs such as HSP (Mickey 1985) which may generate more accurate magnetic flux values but introduce spatial distortions. The data consist of the three components of the magnetic field B (Figure 2). These components are obtained using polarization measurement. To measure the three components of the magnetic field, one has to determine Zeeman splitting of the line profile, (normal Zeeman splitting gives the line of sight component of the magnetic field, while anomalous Zeeman splitting gives the transversal component). The data are corrected for dark offset and flat field,
main spot due to return current, and it is mixed in the following part of the region. These two regions correspond to the same distribution in the map of $B_z$, and $\alpha$ has the highest values there. Some noise in $\alpha$ is present in the region of weak $B_z$, that is close to the edges of the magnetogram. Low noise level appears to be more important than high spatial resolution for the reconstruction of the magnetic field in the corona.

To summarize results from 2D data analysis: We found that:

- $\alpha$ is not constant even on small scales i.e. there are positive and negative values of $\alpha$ in neighboring regions.
- Low resolution may eliminate accuracy on return current.
- We found that the dominant sign of $\alpha$ is positive in AR7912.

This indicates that a main sign of the twist exist as emphasised by Pevtsov et al. (1997).

4. THE METHOD OF RECONSTRUCTION

Let us recall that for a general Force-Free field we have:

$$\nabla \times \vec{B} = \alpha(\vec{n}) \vec{B}$$  
$$\vec{B} \cdot \nabla \alpha(\vec{n}) = 0$$  
$$\nabla \cdot \vec{B} = 0,$$

in the domain $\Omega$ that represents the space region above the magnetogram, which may be taken sufficiently large to mimic the upper half-space.

The boundary data are:

$$B_n|_{\partial \Omega} = b_0$$  

$\partial \Omega$ is the boundary of the domain $\Omega$,

$$\alpha|_{\partial \Omega^+} = h = \frac{(\nabla \times \vec{B})_z}{B_z}$$

where $\partial \Omega^+$ is the part of $\partial \Omega$ where $B_n > 0$. And also we have:

$$\lim_{r \to \infty} |\vec{B}| = 0$$
The existence of solutions (Boulmezaoud, Amari and Maday, 1999) being ensured, the numerical procedure used to solve (1)-(3) is explained in detail in (Amari et al 1996-1999).

We used a non-uniform mesh in the three directions (nx=92, ny=52, nz=39) on the work-station or (nx=148, ny=88, nz=70) on Cray C90 supercomputer. The non-uniform mesh is concentrated in the leading spot and the mixed polarity region. To mimic the boundary conditions of weak remote field, we add some points in each directions, and smooth the data. Full flux-balance is an important condition for a good reconstruction; partial coverage of a full active region, such as with data from HSP for 14 Oct, can lead to erroneous results as the computed magnetic structure is not closed.

5. RESULTS

<table>
<thead>
<tr>
<th>Type of data</th>
<th>pre-flare</th>
<th>post-flare</th>
</tr>
</thead>
<tbody>
<tr>
<td>IVM</td>
<td>1.542E+32</td>
<td>1.018E+32</td>
</tr>
<tr>
<td>Magnetic energy (erg)</td>
<td>4.09E+40</td>
<td>4.37E+39</td>
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</tbody>
</table>

Once the solution is computed fieldlines are compared to soft X-ray coronal loops. We find that:
Coronal field lines reproduce soft X-ray sigmoid as seen by comparison of figures 4 and (5-b).
We compute the relative helicity for the non-linear force-free field calculated above (\(\Delta H = \int_{\Omega} (A - A_0) \cdot (B + B_0) d^2r + \int_{\partial \Omega} K(B + B_0) ds\)) as in (Amari and Luciani 1999). The linear force-free field with the same helicity is also computed. The two fields are strongly different (Figures 5 a, b). This method for determination of the constant-\(\alpha\) in FF fields is more meaningful than to determine \(\alpha\) such as to match coronal X-ray loops. Coronal X-ray loops should be used only for confrontation afterwards.

6. DISCUSSION

Our main result is that the helicity in the AR has decreased after the eruption.
This suggests that the helicity was ejected out of the active region. Coronal plasma has very little resistivity, and we expect that it must then have a conserved global helicity. The fact that the helicity has decreased in the AR may only be explained if some helicity gets out of the computation box. Recent numerical models and MHD simulations (Amari et al. 1996) show indeed this possibility. These models show the opening of the field in a finite time and the ejection of a plasmoid, which corresponds to a twisted flux tube. The final state in these models corresponds to a semi-open configuration, i.e. most of the field lines are open, though some of them remain closed.
In our calculation, the ejected twisted flux tube corresponds to the magnetic cloud, which passes entirely out of the numerical box used for the reconstruction. Taylor (e.g. Taylor 1986) proposed that after an eruption, the magnetic field configuration relaxes to a linear i.e. (constant \(\alpha\)) force-free state. Recall that the Taylor hypothesis would apply for a constant helicity magnetic field configuration, where energy may not change (e.g. due to resistivity). Here helicity is not constant thus ejected to infinity out of the box. Assuming that global helicity would be conserved then Taylor’s hypothesis should apply to the “remaining” helicity.
- Our results show that the Taylor constant \(\alpha\) state is not the state found after the eruption.
- This has already discussed of confined eruption (Amari and Luciani 1999) in the model of a confined eruption.
Helicity is distributed in the boundary of the domain (that is at infinity, in the magnetic cloud).
- Some adequate constraint might be applied to pre-
Our results do not support Taylor's hypothesis that after an eruptive event the magnetic fields relax to a constant-α (linear) force-free state with the same helicity as the former non-linear force-free state. The fact that helicity has decreased after the eruption indicates strongly that there is a large amount of helicity which has been ejected to infinity (in the magnetic cloud), in good agreement with recent numerical results concerning plasmoid ejection.

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7. CONCLUSION

We reconstruct the magnetic field in the corona of the active region NOAA 7912 on 14 October 1995, before and after an eruptive event. The results are consistent with Yohkoh soft X-rays data and WIND spacecraft observation of a magnetic cloud passing the earth on 18-20 October 1995. Magnetic energy and relative helicity of the active region have decreased after the eruptive event.
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