DESCRIBING CORONAL MAGNETIC FIELDS BY SUCCESSIVE FORCE-FREE EQUILIBIA

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ABSTRACT

Solar flares are often related to photospheric motions such as moving features, sunspot rotation, cancelling magnetic features. In active regin 8210 observed on May 1st 1998, we have observed the clockwise rotation of the main sunspot. To understand the coronal response to this photospheric motion, we study the time evolution of the coronal magnetic field configuration near the sunspot where the flares have occurred. We assume that the evolution of the coronal magnetic field can be described by a series of nonlinear force-free equilibria reconstructed from photospheric vector magnetograms. The reconstructed magnetic structures involve field lines in a complex topology (e.g. null points, separatrix surface). The photospheric motion has moved the sunspot magnetic field lines towards the separatrix surface. As evidenced by the evolution of the reconstructed magnetic field, the above motion has led to reconnection process near the separatrix surface and associated with Hα blueshift events.

Key words: Sun: flares; Sun: magnetic field, Sun: MHD.

1. INTRODUCTION

To better understand the physics of flare, we need to determine the 3D magnetic field configuration in the corona and also to follow the evolution in time before and after the eruptive event. We recently describe a new technique to study the evolution of an active region by successive nonlinear force-free equilibria (Régnier & Canfield, 2005). We apply this technique to the active region 8210 observed on May 1st 1998. Between 17:00 UT and 21:30 UT, AR 8210 has produced 5 C-class flares and 1 B-class flare. In Régnier & Canfield (2005), we have studied the correlation between the flare sites, the Hα blueshift events and the coronal magnetic configurations.

2. DETERMINING THE CORONAL MAGNETIC FIELD

2.1. Data

We focus our study on the highly flare-productive active region 8210 observed on May 1st 1998 between 17:00 UT and 21:30 UT near the disc center. For this time period, a time series of vector magnetograms recorded by MSO/IVM (Mickey et al., 1996) is available. The reduction process as well as the main characteristic of this dataset are described in detail in Régnier & Canfield (2005). In order to follow the time evolution of the active region, we cross-correlate the images. Each photospheric vector magnetogram corresponds to the same surface which means that the same coronal volume is used to compute the nonlinear force-free field.

2.2. Reconstruction Method

To determine the magnetic configurations, we assume that the magnetic field is force-free in the corona (low plasma β). The definition of the force-free field is given by the two following equations:

$$\vec{\nabla} \wedge \vec{B} = \alpha \vec{B}, \quad (1)$$

$$\vec{B} \cdot \vec{\nabla} \alpha = 0. \quad (2)$$

For a nonlinear force-free field, α is a function of the position and is a constant along a given field line as shown by Eqn. (2). To solve the boundary value problem associated with these equations, we use the numerical scheme proposed by Grad & Rubin (1958). The method was rewritten by Amari et al. (1997, 1999) in terms of the vector potential $\vec{A}$ ($\vec{B} = \vec{\nabla} \wedge \vec{A}$) to insure the solenoidal condition ($\vec{\nabla} \cdot \vec{B} = 0$). The Grad & Rubin iterative scheme can be written as follows:

$$\vec{\nabla} \wedge \vec{A}^{(n)} \cdot \vec{\nabla}\alpha^{(n)} = 0 \quad in \quad \Omega, \tag{3}$$

$$\alpha^{(n)}|_{\partial\Omega^{\pm}} = \alpha_0 \quad in \quad \partial\Omega \tag{4}$$

where Ω is the coronal volume and $\partial\Omega$ is the associated boundary and

$$-\vec{\Delta}\vec{A}^{(n+1)} = \alpha^{(n)}\ \vec{\nabla} \wedge \vec{A}^{(n)} \quad in \quad \Omega, \tag{5}$$

$$\vec{A}_t^{(n+1)} = \vec{\nabla}^{\perp}\chi \quad on \quad \partial\Omega, \tag{6}$$

$$\partial_n \vec{A}_n^{(n+1)} = 0 \quad on \quad \partial\Omega, \tag{7}$$

$$\lim_{|r|\to\infty} |\vec{A}^{(n+1)}| = 0. \tag{8}$$

In the above systems of equation, α_0 is the distribution of α derived from the data and monotically increased during the iterative process. This method corresponds to a slow injection of electric current density inside the magnetic configurations. The result of this method is the improve the stability and the convergence of the code. The operator $\vec{\nabla}^{\perp}$ is defined on $\partial\Omega$ such as $\vec{\nabla}^{\perp} \cdot \vec{\nabla} = 0$. χ is the unique solution of

$$-\Delta_{\perp}\chi = b_0 \quad on \quad \Omega, \tag{9}$$

$$\chi = 0 \quad or \quad \partial_n\chi = 0 \quad on \quad \Gamma \tag{10}$$

where $\Delta_{\perp}$ is the Laplacian operator on $\partial\Omega$ and Γ is the border of $\partial\Omega$. b_0 is the magnetic field distribution of the normal component to $\partial\Omega$.

Pratically, we use the photospheric vector magnetograms described in the previous Section to prescribe the bottom boundary conditions: the vertical component of the magnetic field in both polarities and the distribution of α in one polarity. On the other sides of the computational box, we impose that $\vec{B} \cdot \vec{n} = 0$ (same as Eqn. 8).

3. ROTATING SUNSPOT IN AR 8210

From the time series of 3D magnetic field configuration, we follow the evolution of AR 8210 at the site of the flaring activity. In Fig. 1, we first notice that two systems of field lines are easily identified and then two domains of connectivity can be defined: domain A (red field lines) connecting the negative sunspot and the positive polarities on the East side of AR 8210, and domain B (green field lines) connecting the negative sunspot and a diffuse positive polarity on the West side (outside the selected field-of-view). In terms of magnetic field topology, we can conclude that there is a separatrix surface dividing the two domains of connectivity. In Fig. 2, we plot two different domains : domain A (red field lines on the right) similar to the one in Fig. 1, and domain C which contains field lines connecting the negative sunspot and a positive polarity on the North-East part of AR 8210. We again notice that there is a separatrix surface dividing the two domains. In addition a null point is located on the photosphere between those two domains (see Régnier & Canfield, 2005).

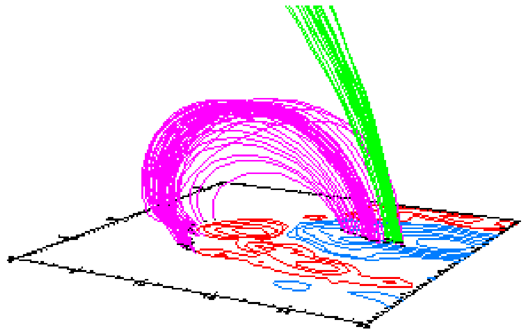

Figure 1. 3D view of few field lines defining the connectivity domains in the vicinity of the flare site. Blue (red) contours indicate the negative (positive) polarities. Red (green) field lines are connected in domain A (B).

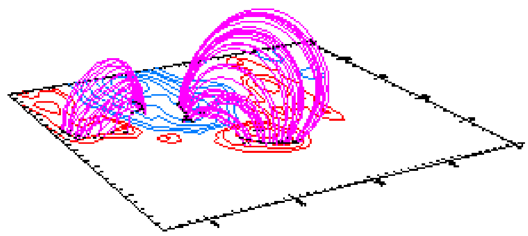

Figure 2. 3D view of few field lines defining the connectivity domains in the vicinity of the flare site. Blue (red) contours indicate the negative (positive) polarities.

In Fig. 3, we plot the time series of reconstructed field lines in domains A and B (as described in Fig. 1). In particular, we note the change of connectivity around (i) image #2 (first row second column at 17:31 UT) and (ii) image #11 (third row first column at 20:42 UT). The case (i) is related to blueshift events before the flare at the location of the separatrix surface with a footprint in the negative sunspot. The associated flare has a rising phase starting at 17:32 UT. The case (ii) is not related to blueshift events but only with a C 2.8 flare starting at 20:25 UT and ending at 20:40 UT. Both cases evidence a reconnection process along the separatrix surface dividing domain A and domain B.

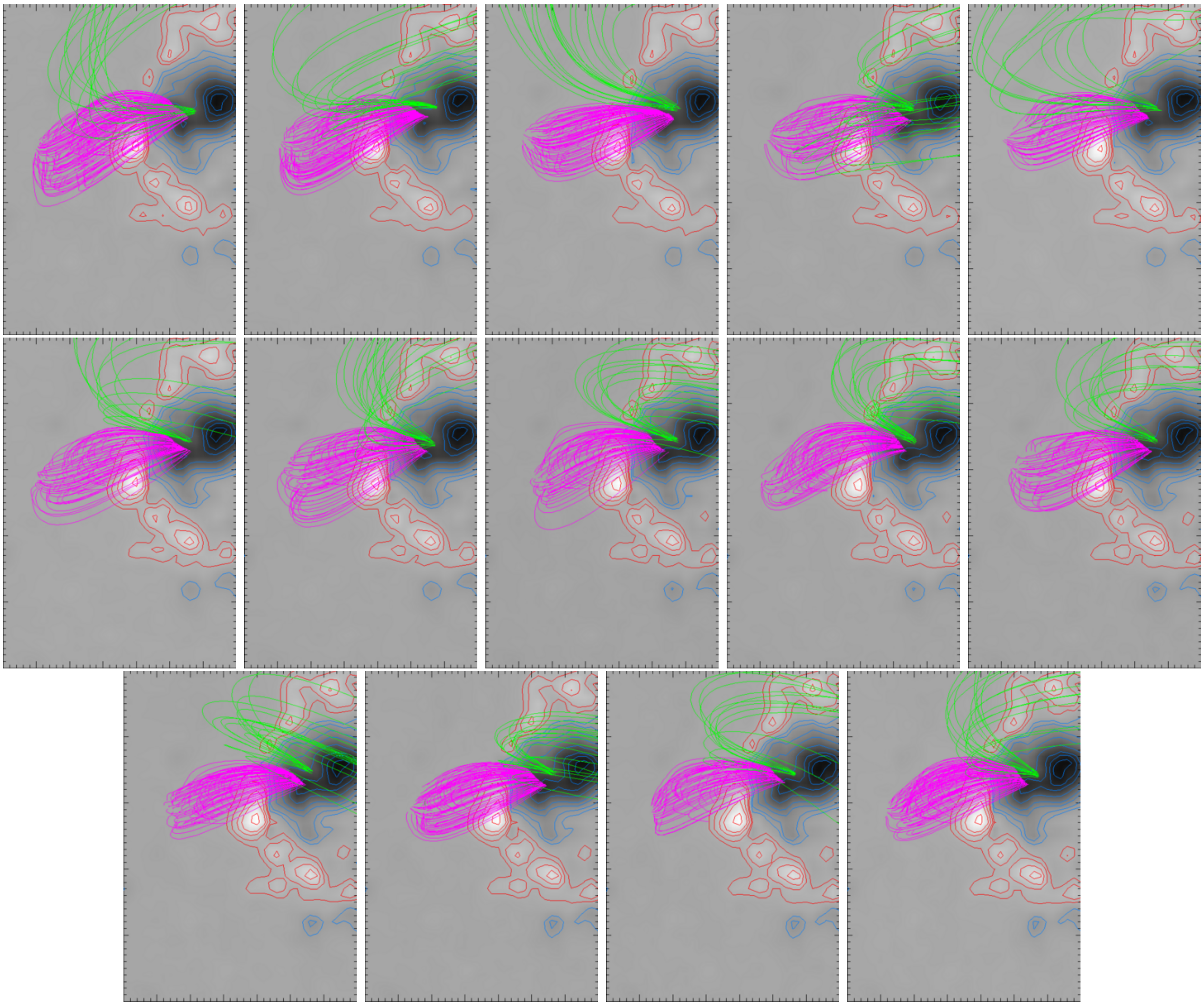

Figure 3. Time evolution of the magnetic configuration due to the clockwise sunspot rotation. Red (green) field lines define the connectivity A (B).

4. DISCUSSION AND CONCLUSIONS

We have developed a new technique to study the time evolution of active regions by successive equilibria. This technique is based on the nonlinear force-free modelling and the measurement of vector magnetic field at the base of the corona. Using this technique we have shown that the flaring activity in AR 8210 on May 1st 1998 between 17:00 UT and 21:30 UT comes from the existence of a separatrix surface in the negative sunspot and is a consequence of the slow rotation of the sunspot.

ACKNOWLEDGMENTS

S. R.'s research is funded by the European Commission's Human Potential Programme throught the European Solar Magnetism Network (contract HPRN-CT-2002-00313). The computations have been performed on a V880 Sun computer supported by the DoD/AFOSR MURI grant "Understanding Magnetic Eruptions and their Interplanetary Consequences".

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Régnier, S., Canfield, R. C. 2005, A&A, submitted