HOW IS MAGNETIC ENERGY STORED AND RELEASED?

S. Régnier(1) and R. C. Canfield(2)

(1)ESTEC–ESA, 2200 AG Noordwijk, The Netherlands
(2)Physics Department, 264 EPS Building, Montana State University, Bozeman, MT, 59715, USA

ABSTRACT

One key issue to understand the coronal heating problem is to know how magnetic energy can be stored and then released in a solar magnetic configuration. We focus our study on the existence of magnetic structures and topological elements that are associated with eruptive events in the corona. We first observe a twisted flux tube in active region (AR) 8151 which is associated with an eruption. The kink instability is the important mechanism to release the magnetic energy easily stored in a twisted flux tubes. And secondly we follow the time evolution of AR 8210 in which the complex topology and the photospheric transverse motions trigger some C-class flares. In AR 8210, two photospheric motions are considered as pre-flare phenomena: the clockwise rotation of the main sunspot and the fast moving parasitic polarity. Our observations imply that only the sunspot rotation is able to store a sufficient amount of magnetic energy to produce a detectable flare. The combination of photospheric motions and the existence of appropriate topological elements is also important for storage and release of magnetic energy.

Key words: Sun: corona; magnetic fields; flares; magnetic energy.

1. INTRODUCTION

One key element to understand the physical processes in the solar corona is the 3D structure of the magnetic field. To determine the coronal magnetic configuration, we use a nonlinear force-free reconstruction method using vector magnetograms as photospheric boundary conditions. In combination with chromospheric and coronal (EUV and X-ray) observations, we can infer the dynamical properties of an active region, especially the response of the coronal magnetic field to transverse photospheric motions.

2. MAGNETIC DATA

For AR 8151, we use one vector magnetogram observed by IVM on February 11, 1998 at 17:36 UT. AR 8151 is an old active region with decaying magnetic flux. The photospheric distribution looks like a dipole with a leading negative sunspot and a following diffuse positive polarity (Régnier, Amari & Kersalé 2002).

For AR 8210, we analyse a time series of 14 vector magnetograms observed by IVM on May 1, 1998 from 17:13 UT to 21:29 UT. The active region has complex distribution of the photospheric magnetic field: the main negative sunspot is surrounded by positive polarities.

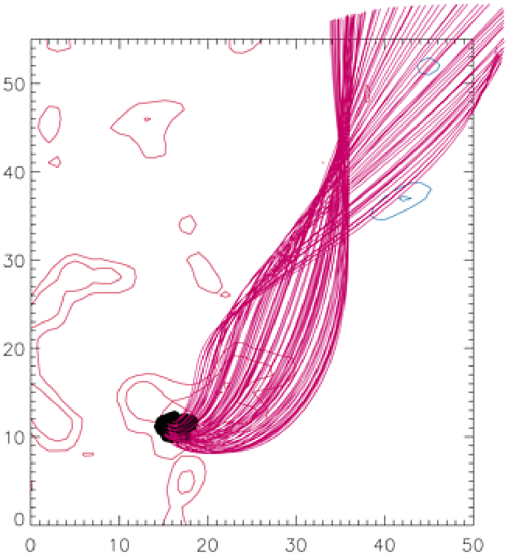

Figure 1. Highly twisted flux tube reconstructed inside AR 8151. The number of turns is 1.2. Only the part with a footpoint in the positive polarity is plotted.

In both cases, we have extended the IVM field of view by surrounding it using a MDI line-of-sight magnetogram. The main effect is to confine the magnetic field above the active region. The vector magnetograms are in the disk-center heliographic coordinate frame. The spatial resolution is of 1.1”. We determine the coronal magnetic field by assuming that the corona at the time of observing is considered as a nonlinear force-free equilibrium. We impose that $\vec{B} \cdot \vec{n} = 0$ on the sides of the computational box different from the photosphere. It is worthnotice that for the time series the reconstruction is valid because the time cadence is higher than the Alfvén time and because the line profiles are not strongly modified by huge flaring activity (e.g., strong Doppler shifts).

3. TWISTED FLUX TUBE

In Régnier, Amari & Kersalé (2002) and Régnier, Amari (2004), we study in detail the structure of AR 8151. Especially we focus our purposes on the existence of twisted flux tubes inside the magnetic configuration. Two twisted flux tubes have been identified to the Hα filament and the X-ray sigmoid observed in the corona. Those twisted flux tubes have a small number of turns ($\sim$ 0.5 turns) and have opposite electric current density. In addition, a highly twisted flux tube was found with a number of turns greater than one (see Fig. 1). We conclude that the most likely eruption process is for this event the kink instability which can be developed in the highly twisted flux tube. The filament and the sigmoid have a passive role. Nevertheless the existence of the filament and of the sigmoid is a good indication of high electric currents and twisted flux bundles.

It is worthnotice that a twisted flux tube is a simple magnetic structure which allows to store magnetic energy into the corona (Priest , 1984). And the energy release can be done by two different ways: the active role of the twisted flux tube (e.g., kink instability), or the passive role (e.g., tether cutting, breakout model)

4. PHOTOSPHERIC MOTIONS AND TOPOLOGICAL ELEMENTS

We investigate the link between photospheric motions, topological elements and flaring activity in AR 8210. We follow the time evolution of AR 8210 observed on May 1, 1998 from 17:13 UT to 21:29 UT. We use a large set of data to understand the flare phenomena. The X-ray flux measured by GOES-8 exhibits numerous C-class flares during this time period (Régnier & Canfield , 2004). The source of the flares are determined by chromospheric Hα observations (MCCD/MSO) and coronal EUV and X-ray observations (EIT/SOHO, SXT/Yohkoh). In addition, the Hα spectroheliograms provide us the location of blueshift events which are the chromospheric counterpart of a reconnection process in the low corona (Canfield & Reardon , 1998; DesJardins & Canfield , 2003). In Fig. 2, the photospheric distribution of the magnetic field observed by IVM shows a negative sunspot surrounded by positive polarities. The A and flare sites are the sites of flaring activity: A is location of most of the C-class flares and the flare site is the location of the C2.8 flare at 20:32 UT. Below, we study the evolution of the coronal magnetic field configuration in the vicinity of site A where the effect of the sunspot rotation is the most important, and for the moving feature (see Fig. 2).

4.1 Sunspot rotation

The long term evolution ($>$ 5 days) shows that the negative sunspot is rotating clockwise wih a rotation rate of few degrees per day. At the same time the South-East positive polarity (including the site of flare in Fig. 2) is moving southward.

In Fig. 3, we have the time series of 3D coronal magnetic field where the effect of the sunspot rotation is the most important. We have 14 snapshots of AR 8210 from left to right and top to bottom. We only plot few field lines which characterize the geometry and the topology of this area. On one hand, the red field lines characterize a system of loops inside a unique connectivity domain (domain A, say). Those field lines are not really modified during the evolution. On the other hand, the green field lines characterize a system of loops which is connected to the West side of AR 8210 (domain B, say) and which significantly evolves in time. A separatrix surface (dome-like surface) divides the domain A and B.

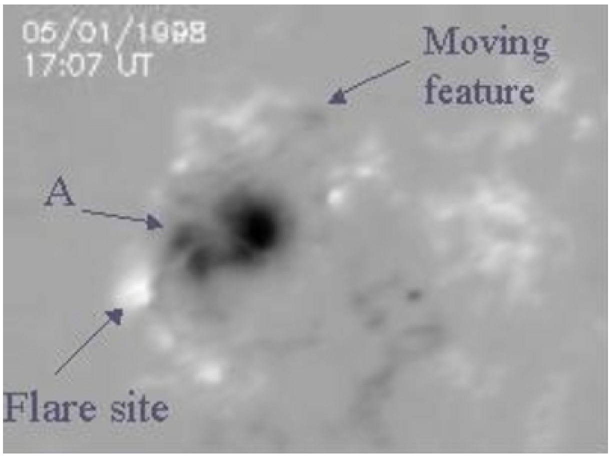

Figure 2. IVM vertical magnetic field distribution of AR 8210 on the photosphere at 17:07 UT on May 1, 1998. The sites A and F indicate the location of Hα blueshift events and of flaring activity respectively. The fast moving parasitic negative polarity is also shown.

The main changes in the magnetic configuration are observed at 18:01 UT (first row, third column in Fig. 3). These changes in connectivity appear after a series of Hα blueshift events (Régnier & Canfield , 2004). Due to the observed photospheric motions and the coronal changes, we have the following scenario for a series of C-class flares:

- the clockwise rotation of the sunspot moves the field lines in domain A toward the separatrix surface;
- magnetic energy can be stored close to the separatrix surface;
- when enough energy is stored, a reconnection process occurs on the separatrix surface reconnecting field lines from domain A to domain B.
- the amount of magnetic energy released in kinetic energy during the reconnection process produces C-class flares.

The separatrix reconnection process induced by the relatively slow sunspot rotation is sufficient to trigger a small scale flare in AR 8210. The process occurs at an intermediate scale (between 15 and 30 Mm) in the low corona.

4.2 Emerging, moving feature

On the North-West side of AR 8210, a parasitic negative polarity has emerged (see Fig. 2). This polarity is also

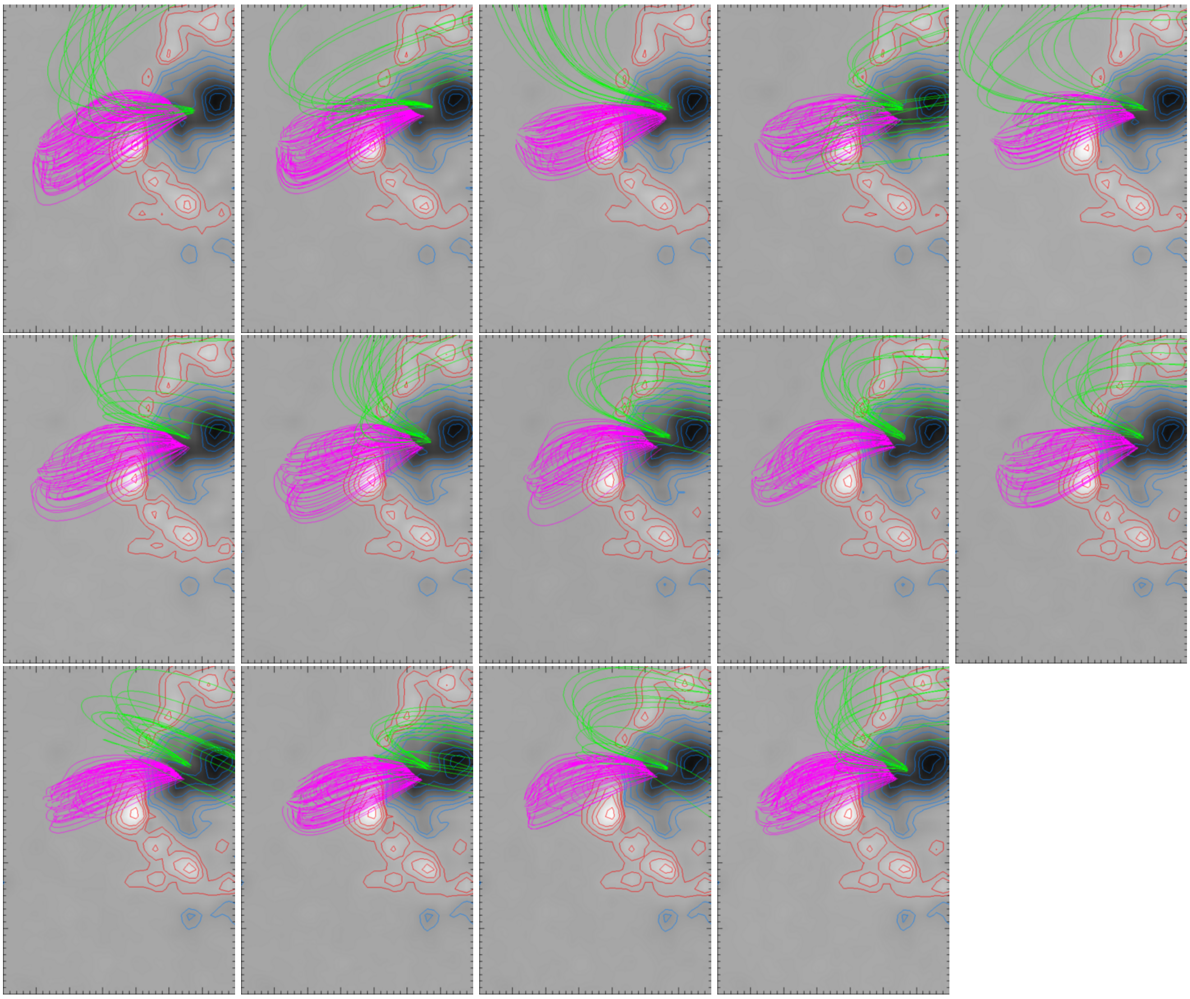

Figure 3. Time evolution of the magnetic configuration due to the sunspot rotation. See text for detail.

moving toward the South-West with an estimated horizontal speed of 0.7 km.s^{-1}. We study the evolution of the connectivity around this fast moving polarity.

In Fig. 4, we plot the evolution of the coronal magnetic field in around the parasitic negative polarity. The red field lines correspond to the pre-existing magnetic topology connecting the sunspot (South-East negative polarity) and the two positive polarities. The field of view is then divided into two connectivity domains by a separatrix surface. The parasitic negative polarity emerges close to the separatrix surface and then moves toward the South-West of the image. The green field lines are few field lines connecting the moving polarity into the two connectivity domains. When the negative polarity is moving toward the South-West, less and less green field lines are connected into the North-East connectivity domain (see Fig. 4). We conclude that a reconnection process takes place at the location of the separatrix surface which allows the field lines into the North-Easst domain to be reconnected into the South-West domain. Nevertheless no chromospheric or coronal counterpart to the reconnection process is observed. We conclude that the fast motion of the parasitic polarity is not able to store a sufficient amount of magnetic energy into the corona to trigger observable flares.

5. DISCUSSION AND CONCLUSIONS

In this article, we study the magnetic configurations of two different active regions which have produced an eruption. First, an old decaying active region (AR 8151) contains numerous twisted flux tubes with different twist value and electric current density. Especially, one highly twisted flux tube is believe to trigger the eruptive process by the development of a kink instability. Second, a complex active region producing numerous flares provides a scenario of flaring activity implying photospheric transverse motions and the topological elements such as separatrix surfaces.

Using a nonlinear force-free modelling from vector magnetograms, we have identify two sources of magnetic energy storage (twisted flux tubes and photospheric transverse motions) and two mechanisms of energy release (kink instability and reconnection along separatrix surfaces). We still need to understand the build-up of mag-

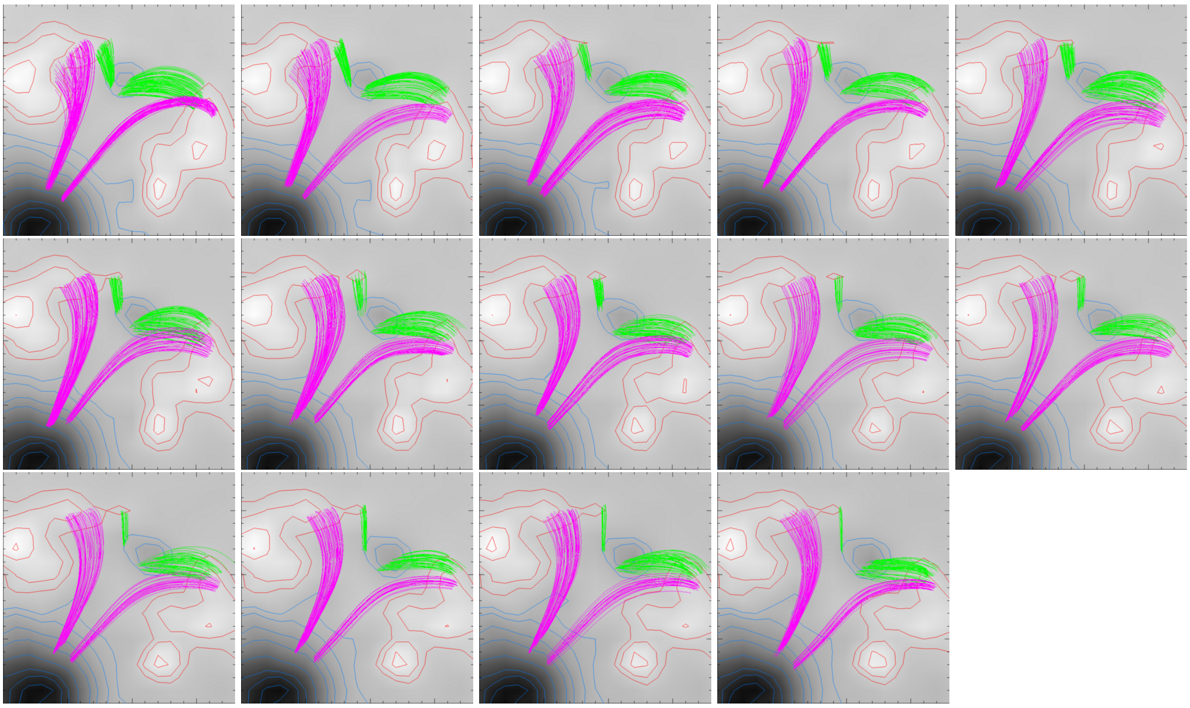

Figure 4. Time evolution of the fast moving parasitic polarity. See text for detail.

netic energy inside a magnetic configuration which can be responsible of large flares.

6. FUTURE OBSERVATIONS

To perform a nonlinear force-free reconstruction, we have the following requirements:

- the **whole** active region should be in the field of view. That implies a field of view of (at least) 300”×300” which is the typical size of an active region;
- the total magnetic flux should be balanced to ensure that $\vec{B} \cdot \vec{n} = 0$ is a good assumption;
- the transverse magnetic field should be well determined. That implies to increase the polarimetric resolution which is often of 10^{-3} giving a threshold on the transverse field of more than 150 G (without averaging on longer time period);
- the spatial resolution is not a big issue because currently the computer (or our algorithm) cannot support a very large grid. Currently the unparallelized code uses 2 GB of memory during 15 days for a grid of 200x200 pixels on the photosphere and 150 pixels in height;
- the line used to deduce the magnetic field vector should be well known in terms of radiative properties and essentially optically thin to ensure the magnetic field is measured at a given photospheric (or chromospheric) height.

We conclude that we have to find a compromise between the spatial resolution and the field of view, the time cadence and the spectral resolution.

To perform a dynamical study as explained in this article, we also need to have a good temporal coverage of less than 15 min to analyse dynamical process as the evolution of the quiet sun or the coronal heating by photospheric motions and small scale reconnections (we also have to remove the magnetic field fluctuations due to photospheric and chromospheric oscillations).

ACKNOWLEDGMENTS

This research is funded by the DoD/AFOSR Solar MURI grant, ”Understanding Magnetic Eruptions and their Interplanetary Consequences”, and by the European Commission’s Human Potential Programme through the European Solar Magnetism Network (contract HPRN-CT-2002-00313).

REFERENCES

Canfield, R. C., Reardon, K. P., 1998, Sol. Phys., 162, 145

DesJardins, A. C., Canfield, R. C., 2003, ApJ, 598, 678

Priest, E. R., 1984, in Solar Magneto-Hydrodynamics

Régnier, S., Amari, T., Kersalé, E., 2002, A&A, 392, 1119

Régnier, S., Amari, T., 2004, A&A, 425, 345

Régnier, S., Canfield, R. C., 2004, in preparation