VELOCITY FIELDS IN A SOLAR ACTIVE REGION

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Abstract. We analyze a solar active region that produced multiple flares, using data from SOHO spacecraft. Our attention is drawn on the photospheric flows and the helicity evolution during the explosive events occurrence. We have computed the velocities filed by the Local Correlation Tracking (LCT) algorithm, in order to compare them for time before and after a flare occurrence. We also extrapolated the coronal magnetic field from the photospheric magnetograms and estimated the force-free-field alpha parameter that expresses the torsion of the magnetic field lines, for both moments.
The magnetic field is modeled as dipoles, and by applying the Powells method, the dipoles positions are detected on an observed magnetogram of the active region. After determining the dipoles, the magnetic field lines are drown in Cartesian coordinates. Estimation of the parameter alpha, as a measure of the torque of the magnetic field lines, is made at different times in the idea to detect the magnetic field helicity (measured by the torsion) evolution during the explosive solar events occurred in the active region.
The obtained results shows that the alpha parameter has positive peaks when magnetic flux emerges in the studied region and the coronal loops are open, and becomes negative after the eruptive event produces.

Key words: solar physics – active regions – magnetic field – flows – magnetic helicity.

1. INTRODUCTION

Solar flares and coronal mass ejections are the most spectacular solar phenomena, therefore they have always aroused the interest of researchers in solar physics. Our purpose is to investigate the flows and helicity evolution in an active region, before and after explosive events occurrence. For this we use the most popular method for flows detection, *i.e.*the Local Correlation Tracking (LCT). This method was first developed by Leese *et al.* (1970) for tracking clouds and it was introduced in the solar physics by November and Simon (1988) in their studies for detecting the velocity fields. The LCT method is based on the principle that the local displacement in two consecutive images is determined for each position by cross-correlating of frames within a spatial window. Each image is characterized by the movement x and time t. This method has been applied to many active regions, and different authors has produced results supporting that magnetic helicity injection in active regions is very important for flares and coronal mass ejections occurrence. Chae *et al.* (2001) found that for a filament positioned inside an active region, more magnetic helicity was injected than required for the filament's formation. Magnetic helicity injection was also found to be correlated to filaments' eruption (Romano *et al.*, 2005) and flares' (Moon *et al.*, 2002) and coronal mass ejections' occurrence (Nindos *et al.*, 2003). The LCT method has successfully been used on many different types of data, ground or spatial based, but often it was also criticized. Besides the fact that it works only with certain types of data, its limit is that it is very slow from the points of view of data processing, so it takes a long time. Another disadvantage of method is also that it assumes that the velocity is constant at some positions and disregards of expansions, compressions and twists of the magnetic field lines. Thus, the method has always been improved. There have been developed many "optical flow" methods which intended the improvement and elimination of LCT method's limitations, among which we mention the induction method – IM (Kusano *et al.*, 2002), inductive local correlation tracking – ILCT (Welsch *et al.*, 2004), Fourier local correlation tracking - FLCT (Welsch *et al.*, 2007), minimum energy fit – MEF (Longcope, 2004), differential affine velocity estimator – DAVE (method implemented by Chae *et al.* (2006) with the algorithms and data documented by Schuck (2006)), nonlinear affine velocity estimator - NAVE (Schuck , 2005). All these methods, except FLCT, are based on the ideal induction equation and they are used to track the velocity for different types of data. Welsch *et al.* (2007) made tests of this routine and concluded that DAVE method estimated the magnitude and direction of velocity vector more accurate than other methods. DAVE determines the optical flow by applying the magnetic induction equation and an affine velocity model statistically to a subregion of the magnetogram sequence which produce a system of equations that can be solved by standard least squares method. The DAVE method is modified to directly incorporate the horizontal magnetic field and produce a differential affine velocity estimator for vector magnetograms, named DAVE4VM (Schuck , 2008). Nevertheless, the LCT method allows quantitative correlation of magnetic flux motion with magnetic helicity in the solar active regions.

The term of magnetic helicity was introduced by Elsasser (1956). The magnetic helicity in the solar atmosphere has been a quantitative instrument for characterization of the helical nature of the magnetic field. It is now regarded as an important physical quantity to understand the solar magnetic activities, studying solar flares and coronal mass ejections. Berger and Field (1984) defined the relative helicity that determines the overall twist of a magnetic field anchored in the solar photospheres. Unfortunately, the relative helicity is not directly measurable, because it depends on the magnetic field throughout as an entire coronal volume.

The helical structures are observed in the solar atmosphere (photosphere, chromosphere, and corona). There are several methods to calculate the magnetic helicity injection, applied by Chae *et al.* (2001), Kusano *et al.* (2002), Démoulin and Berger (2003), Welsch *et al.* (2004), and Longcope (2004). Chae *et al.* (2001) applied the

LCT method to estimate the tangential velocity V_t in the solar photosphere. They calculated the helicity injection only from shearing motions. Kusano *et al.* (2002) introduced the induction equation to calculate the longitudinal velocity V_n component. This V_n produces an electric field that explains the temporal evolution of the longitudinal field strength. They calculated the helicity injection rate both from shearing motions V_t and the emergent motions V_n.

If plasma velocity $V_t = 0$ then

$$V_{LCT} = \frac{-V_n}{B_n} \cdot B_t \tag{1}$$

and if $V_t \neq 0$ then

$$V_{LCT} = V_t - \frac{V_n}{B_n} \cdot B_t \tag{2}$$

where B_n and B_t are the normal and tangential components of the magnetic field B.

The sign of magnetic helicity on the photosphere was determined by calculating the alpha best values (α_{best}) by Pevtsov *et al.* (1995), the averaged alpha (α_z) by Pevtsov *et al.* (1995) or (α_{av}) by Bao and Zhang (1998) and Hagino and Sakurai (2005). Between alpha best and averaged alpha was found a good correlation (Burnette *et al.*, 2004; Leka *et al.*, 1996).

The study of the helicity in the solar active regions is important for understanding the solar dynamo processes and the build up of the energy in the explosive events like flares and coronal mass ejections.

Although the LCT method have serious limitations, it remains a widely used method and because it can be used on various types of data it gives added value. Chae *et al.* (2001) studied the possible errors of method and he found that these errors are localized and they do not affect results only at a rate of 10%.

In the present work, we analyzed the evolution of the solar active region NOAA 10930, that produced a large number of flares, including a X3.4 flare accompanied by a coronal mass ejection and we computed the plasma flow by means of LCT method. We also estimated the force-free parameter, representing the torsion, like a measure of the helicity, in order to highlight what happened during a complex eruptive event such as a big flare, source of a coronal mass ejection (CME).

2. ANALYSIS OF THE ACTIVE REGION NOAA 10930

The active region NOAA 10930 (named also AR10930) is a large active region observed in the decline phase of solar cycle 23. It was visible in the Southern hemisphere of the Sun, between 6 December and 17 December 2006. On 11 December, the active region was located near the disk center (S04, E00), at 11:10 UT, and it developed 29 solar flares, from which 24 flares of class C, 3 flares of class M and 2 flares of class X. On 13 December, it produced a halo CME, and that was the largest halo observed after the Hallowen solar storm (October - November 2003, Richardson *et al.*2005).

Figure 1 displays the SOHO/MDI magnetogram on 13 December 2006, with a focus on the active region AR10930.

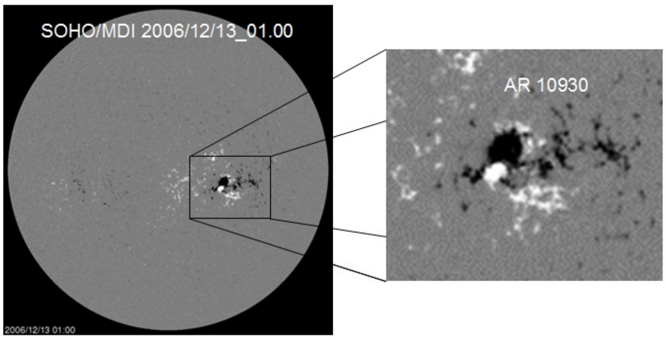

Fig. 1 – SOHO/MDI magnetogram on 13 December 2006 and the active region AR10930 on time 01:00 UT.

The CME had a speed of 1774 km s^{-1}, mentioned in LASCO CME catalogue (`http://cdaw.gsfc.nasa.gov`), and it was accompanied by radio busts. Actually it was a huge magnetic cloud (MC) that produced significant space weather effects.

The CME, observed by the Large Angle Spectroscopic Coronograph (LASCO), and the active region's coronal observations from the Extreme ultraviolet Imaging Telescope (EIT), both instruments aboard of the SOlar and Heliospheric Observatory (SOHO), are displayed in Figure 2.

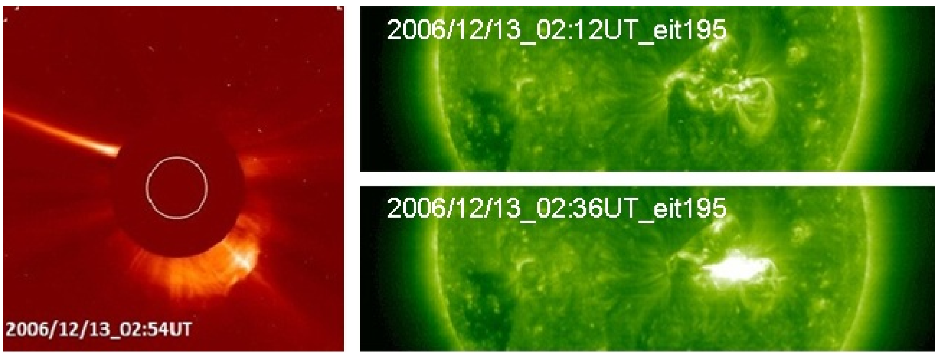

Fig. 2 – Left panel: the SOHO/LASCO C2 observation on 13 December 2006 at 02:54 UT. Right panel: the SOHO/EIT observations of the solar flare evolution.

The flare started at 02:14 UT and ended at 02:57 UT, with the maximum at 02:40 UT. In this day, the active had the coordinates (S23, W05) on the solar disk.

The shear of the magnetic field lines associated to a filament eruption triggered a two ribbons flare. The magnetic field lines were twisted, but largely horizontal around the filament channel, as Zhang *et al.* (2007) have shown.

For tracing movements of unsteady transverse magnetic field lines in the photosphere, we must compute $V_{LCT}(r,t) = r/t$, with r = movement and t = cadence. For this we used vector magnetograms by SOHO/MDI with a cadence of 96 s. The transverse velocity field of magnetic patterns was determined with LCT method and this is displayed in Figure 3, on the left and on the right, is presented the 3D extrapolation of the coronal magnetic field before producing solar eruption, observing for this moment, closing the magnetic field lines and see their opening in figure 4.

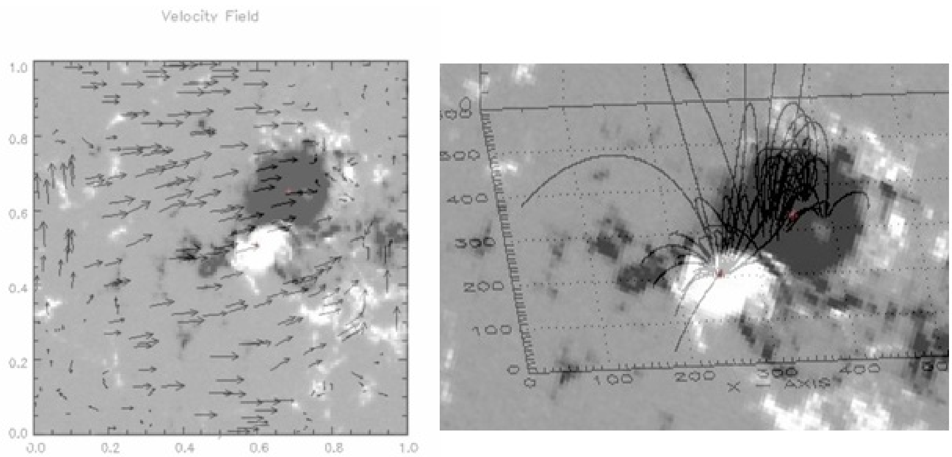

Fig. 3 – Velocity field on 13 December 2006 on the left and 3D extrapolation of the coronal magnetic field on the right.

The helicity can not be directly computed from the formula:

$$H = \int A \cdot B \mathrm{d}x \tag{3}$$

where A = potential magnetic field vector and B = magnetic field, because this formula has an integral of volume and the photospheric observations are in two dimensions. Much more, the magnetic field vector is not uniquely determined, so H has not an unique value.

The helicity of magnetic field can be characterized by the free force parameter alpha, also known as the twist parameter, which gives a measure of the helicity.

The authors that we previously remind have concluded that the sign of helicity in the photosphere is the same with that of the alpha best or of the averaged alpha. For the alpha parameter computation we used a method previously applied in Dumitrache *et al.*(2012), by extrapolating the coronal magnetic field from the photospheric one. The computed 3D magnetic field lines B_x, B_y, B_z, in a $512 \times 512 \times 300$ mesh, served us to infer the α parameter for each moment of observation.

Using the full disk magnetograms from SOHO/MDI, we selected the active region zone in a mesh 512×512. The Powell method was applied to locate the dipoles in the plan $(z = 0)$, by means of min/ max local, in the points of magnetogram where B_z has the highest positive or negative value.

The dipole magnetic field components, (B_x, B_y, B_z), in the Cartesian coordinates, are

$$\begin{aligned} B_x &= B_0 \frac{3xz}{r^5} \\ B_y &= B_0 \frac{3yz}{r^5} \\ B_z &= -B_0 \frac{1 - \frac{3z^2}{r^2}}{r^3}, \end{aligned} \tag{4}$$

r is the magnitude of the position vector: $r = \sqrt{(x^2 + y^2 + z^2)}$, B_0 is the strength of the magnetic field. The force-free field parameter is given by the formula:

$$\alpha = \frac{1}{B_z}\left(\frac{\mathrm{d}B_y}{\mathrm{d}x} - \frac{\mathrm{d}B_x}{\mathrm{d}y}\right). \tag{5}$$

For these computations we have used an IDL code written by J. K. Lee (2002) and modified by us for our purpose (Dumitrache *et al.*, 2012). As a result we obtained the 3D coronal magnetic field configurations at different moments, and figure 4 displays the 3D extrapolations of the coronal magnetic field lines from MDI magnetograms.

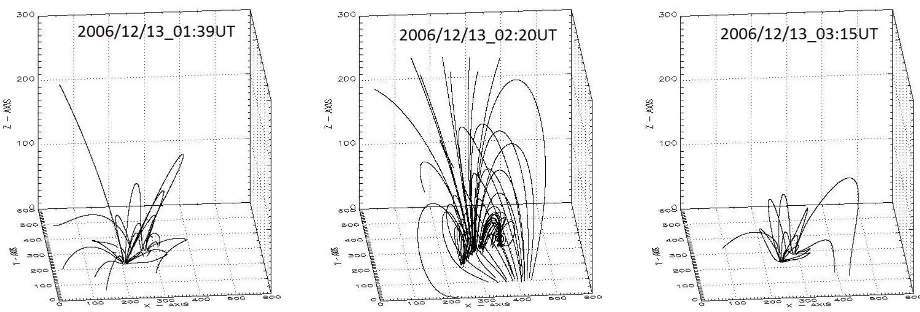

Fig. 4 – 3D extrapolations of the coronal magnetic field for AR 10930 on 13 December 2006 for three different times: before, during and after solar eruption.

We estimated the alpha parameter at different time moments during the evolution of AR10930, before and after the moment of the flare occurrence. Figure 5 displays the results of these computations. We remark positive fluctuations of α at the beginning of the flare, when magnetic flux lines emerge, and negative variations when the magnetic field lines open after the flare occurrences. This result is consistent with the previous one, obtained in Dumitrache *et al.*(2012).

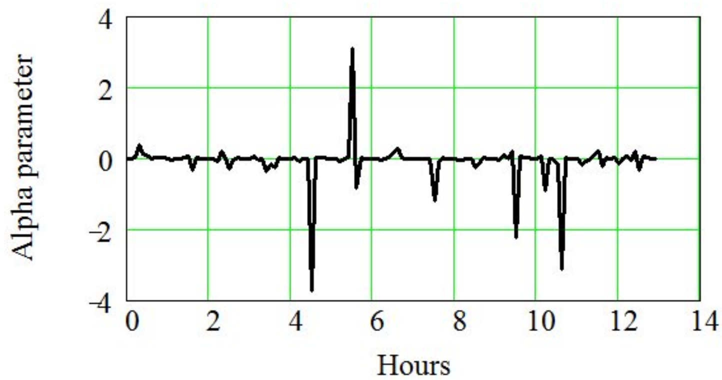

Fig. 5 – The computed force-free field parameter values for AR10930, starting with 00:00 UT, on 13 December 2006.

For α estimated on each pixel, we calculated $\alpha_g = (\frac{1}{N})\sum\alpha$, α_g, that is a global value of α, for complete active region and N is total number of pixels. We found the values of α in the range between $-3.8 \cdot 10^{-8}$ to $2.6 \cdot 10^{-8}$ m^{-1}, while $\alpha_g = -1.5 \cdot 10^{-8}$ m^{-1} value. The α sign gives the sign of the magnetic helicity of the sunspot and α_g gives the axial gradient of the twist of sunspot under the force free conditions (Tiwari *et al.* (2009)).

3. CONCLUSIONS

Using the LCT method, we have computed the velocity field of the photospheric flows aroused at a class X 3.4 flare, observed in AR 10930, on 13 December 2006.

We have estimated the twist of the coronal magnetic field lines by computing the force-free field parameter at different moments of 13 December 2006 event, using the 3D magnetic field extrapolations, and we have calculated the global value of alpha. The variations of parameter indicate positive values at the magnetic flux emergence and negative values after the opening of the magnetic field lines at the explosive events occurrence.

All these results are consistent with our previous works: Dumitrache *et al.* (2012), Dumitru and Dumitrache (2010), Dumitru (2013).

Acknowledgements. This paper was presented at the International Symposium "The Astronomer Nicolae Donici – 140 years after the birth", Bucharest , 8th September 2014.

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Received on 14 May 2015