ROLE OF "X POINT" IN FLARES AND FILAMENT INTERACTIONS

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Abstract. Explaining the trigger and energy release processes of flares is a fundamental problem of solar physics. It is commonly held that magnetic reconnection plays a key role in converting magnetic energy into other forms of energy. In 2D magnetic field configurations, when oppositely directed magnetic fields are brought together they may reconnect thereby releasing stored magnetic energy eventually resulting in a flare. In 3D configurations, the magnetic topology should be considered and the reconnection is favored at the intersection of magnetic quasi-separatrix layers, which is an extension of what is called "X point" in 2D. The evolution of key topological structures, such as null point, spines and fans may determine the eruptive behavior of a flare. The presence of a null point can be very important. We present a few examples, i.e., a flare with a circular flare ribbon and the interaction of two parallel filaments. In the case of flux rope destabilization and triggering eruption due to the torus instability, the important parameter is the decay index and not the topology itself. However the complexity of active regions leads to interpretations where different mechanisms may be intermixed. The breakout mechanism, which requires a quadrupolar configuration with QSLs and separator where the reconnection can occur, is present in many models. That is not always a sufficient condition to explain the eruptive flares. For one case study, the different behaviour of a series of eruptive flares followed by confined flares, all originating in the same site has been attributed to the change of orientation of the magnetic field below the fan with respect to the orientation of the spine. Flares tend to be more confined when the two fields become less antiparallel.

Key words: flares - eruptions - topology

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1. Introduction

Coronal activity such as flares, eruptions and general heating is often attributed to the manner in which the coronal field responds to photospheric motions. A very powerful tool to understand where the energy could be deposited is to study the magnetic topology of the active region, since it defines where magnetic reconnection is expected to occur (see the reviews of Démoulin, 2005; Longcope, 2005). The majority of the pioneer investigations considered a simplified two-dimensional geometry in which magnetic reconnection occurred at an isolated X-point or magnetic null point (Sweet, 1958; Filippov, 1999). Field lines passing at the X-point define two separatries. Magnetic reconnection does not occur only at the null points but rather along separator in the corona. Many papers have appeared based on this 3D approach to explain flares (Démoulin et al., 1993; Mandrini et al., 1995; Schmieder et al., 2007), see Démoulin (2005) for a review. The locations of flare ribbons are understood when the separatrices are found in magnetic configurations modeled with sub-photospheric sources. The magnetic field configuration near a null point typically shows a fan and a spine structures. Fan and spine reconnection solutions around magnetic nulls have been obtained both numerically (Craig and Fabling, 1996; Craig et al., 1999) and analytically (Ji and Song, 2001).

Recent reviews (Schmieder and Aulanier, 2012; Schmieder et al., 2015; Janvier et al., 2015) show that the two main mechanisms for triggering flares and eruptions are the torus instability and the break out. The torus instability is an ideal magneto-hydrodynamic instability that can result in the disruption of the equilibrium of a 3D magnetic flux rope embedded in an external magnetic field (Török and Kliem, 2003; Kliem and Török, 2006; Zuccarello et al., 2015). There is no need of a null point. The second mechanism is the break out due to the onset of a resistive instability (Antiochos et al., 1999; Aulanier et al., 2000). The existence of a null point or quasi separator in the corona is needed for the eruption to occur. The flux in the confining arcade must be larger than the flux of the overlying arcade.

In this paper we define the magnetic topology in active regions (section 2) and the reconnection sites using case studies of flares and filament interaction (section 3). In section 4 we discuss a case study where the difference of behaviour of flares in the same active region (eruptive followed by confined flare) may be due to the change of the mutual orientation of
the magnetic field lines below and above the fan of the null point.

2. Magnetic Topology of Active Regions

In the standard 2D CSHKP model the reconnection operates between two legs of an arcade in an X-type null point. In a 3D configuration, null points can be found in the corona using potential, linear force-free or non-linear force-free extrapolation of the photospheric magnetic field. The bright ribbons are produced by particles accelerated at the reconnection site streaming along the field lines downwards to the chromosphere (Jiang et al., 2013). It is important to analyze the magnetic configuration of active regions to map the different magnetic domains of connectivity, i.e. the separatrices. Separatrices, surfaces separating two domains of connectivity, are the possible reconnection sites. A generalization of separatrices are the quasi separatrix layers (QSLs), volumes where reconnection is possible. In QSLs the gradient of field-line connectivity is sharp, but finite. On the contrary, it is infinite in true separatrices, across which the connectivity is discontinuous. So separatrices can be regarded as the limit of QSLs when their thickness tends to zero. The thickness is characterized by a parameter called the squashing degree $Q$ (Démoulin et al., 1997; Schmieder et al., 1997; Titov et al., 2003; Janvier et al., 2013) which is larger for smaller thicknesses. The intersection of quasi-separatrix layers is contained in a volume called hyperbolic flux tube (HFT) (Titov et al., 2003). The HFT is generally the region where reconnection can occur, thus being a probable site of energy release. The overall magnetic topology of an active region does not depend on the extrapolation method used. That demonstrates the robustness of the topology.

3. Reconnection Sites

The presence of X points can favor the reconnection of magnetic field lines and lead to flares and jets (Guo et al., 2013; Sun et al., 2013; Mandrini et al., 2014). In the following, several case studies are presented showing the role of the null point.
Figure 1: Sketch of the interaction of two parallel filaments under a null point and fan structure from the initial configuration to the successive configurations of the first event and second event. The panels a, b, c, d are represented in 3D, the panels e, f, g, h are in 2D (adapted from Joshi et al., 2016).
3.1. Interaction between two filaments favored by a null point

Joshi et al. (2016) presented observations of the interactions of two filament channels of different chirality and with the parallel magnetic axis occurring three times during the time period from April 18 to 20, 2014. They proved that these interactions were possible only due to the presence of a null point, otherwise the two parallel filaments could only bounce according to Linton et al. (2001). The SDO/AIA 171 Å observations and the PFSS magnetic field extrapolation supports the existence of a fan-spine magnetic configuration with a null point. Joshi et al. (2016) suggested that the reconnection between the field lines surrounding the flux ropes and the overlying coronal fields at the magnetic null point leads to the activation and the partial eruption of the filaments. As the field lines are coming closer to the null point the magnetic reconnection can occur and the hot plasma could move along the outer spine line toward the remote point (Figure 1).

3.2. Hyperbolic flux tubes

An interesting example is the active region NOAA 11158 on 15 February 2011, well documented in many papers, for being the site of the large X2.2 flare (Janvier et al., 2014), and CMEs (Vourlidas et al., 2013; Schrijver et al., 2011). Since the magnetic field configuration is relatively well known, the evolution of the topology of this region shows that it is formed from two active regions. The negative following polarity of the first active region was squeezed by the positive leading polarity of the second active region, with an increasing shear, as we have reported earlier regarding the presence of a strong shear before the flare. The region looks like a quadrupolar region with a large hyperbolic flux tube (HFT) whose neighborhood can be assimilated to that around a null point (Zhao et al., 2014). It suggests the existence of a large hyperbolic flux tube with an X-point and a small flux rope near the solar surface. Below the high-altitude HFT, in the region of high shear (bipolar region) a second local HFT exists below the small flux rope. These two different HFTs are regions favorable for reconnection, one at high altitude related to large scale structures, and one very low. The two brightest flare ribbons overlay the small flux rope in the central part of the region, whereas the secondary ribbons are on the intersections of the large
scale QSLs with the solar surface. It was conjectured that the reconnection of the field lines of the low flux rope reconnects at the small HFT and produces the flare. The secondary ribbons started to be bright after the flare and therefore they were a consequence of the flare with a break out of the field lines at the large HFT.

3.3. Role of null point

The presence of null point is not essential. Some flares may occur without the coronal null point (Démoulin et al., 1994b; Démoulin et al., 1996; Mandrini et al., 2014; Li et al., 2006). In the case described by Mandrini et al. (2014), where a new active region was emerging, the flare ribbons have a complicated shape and could not be explained only by the presence of two nulls. It was nevertheless possible to reproduce the shape of the ribbons by computing the quasi-separatrices using a linear force-free extrapolation.

Li et al. (2006) study the magnetic field evolution and topology of the active region NOAA 10486 before the X1.2 flare of October 26, 2003. 3D extrapolation of photospheric magnetic field, assuming a potential field configuration, revealed the existence of two magnetic null points in the corona above the active region. The authors looked at their role in the triggering of the main flare, by using the bright patches observed in TRACE 1600 Å images as photospheric tracers of energy release associated with magnetic reconnection at the null points. All the bright patches observed before the flare correspond to the low-altitude null point. They have no direct relationship with the X1.2 flare because the related separatrix is located far from the eruptive site. No bright patch corresponds to the high-altitude null point before the flare. They concluded that eruptions can be triggered without the pre-eruptive coronal null point reconnection, and the presence of null points is not a sufficient condition for the occurrence of flares. They propose that this eruptive flare results from the loss of equilibrium due to the persistent flux emergence, continuous photospheric motion and strong shear along the magnetic neutral line. The opening of the coronal field lines above the active region (break out) should be a byproduct of the large X1.2 flare rather than its trigger.
4. Breakout Mechanism

Zuccarello et al. (2016) presented a case-study of eruptive flares followed by failed eruptions occurring on April 15 and 16, 2014 in the active region NOAA 12035. The connectivity of the different flux domains and their evolution were computed in a potential magnetic configuration. The quasi-separatrix layers retrieved from the extrapolation fitted well with the flare ribbons (Figure 2). A null point was detected with fan and spines for the
two days with little changes which could not explain the eruptive versus non-eruptive behavior of the series of flares in the active region. The change of behavior of the flares has been attributed to the change of orientation of the magnetic field below the fan with respect to the orientation of the overlaying spine, rather than an overall change in the stability of the large scale field. Theoretical models have shown the importance of the orientation of the magnetic field lines in the reconnection process (Archontis and Hood, 2012). Flares tend to be more-and-more confined when the field that supports the filament and the overlaying field gradually become less-and-less anti-parallel, as a direct result of changes in the photospheric flux distribution. In that region the leading positive polarity has a clockwise rotation while the negative flux was emerging with a motion in the reverse direction introducing a strong shear between the two polarities.

5. Conclusion

It is important to analyse the magnetic topology of an active region to understand where the flares can occur. The topology is robust and does not depend on the extrapolation method in a first approach. The existence of a X point (null point, quasi separatrix, HFT) is a necessary condition but it does not explain all the cases. We have shown that in one case study the role of the X point was not essential. In another case study the orientation of magnetic field lines below and above the X point could have played an non negligible role.

Acknowledgements

We wish to thank the LOC and SOC of Hvar Astrophysical Colloquium for their support and respective contribution to the success of this conference. The work of F.P.Z. is funded by a contract from the AXA Research Fund. F.P.Z. is a Fonds Wetenschappelijk Onderzoek (FWO) research fellow.

References

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