Complex magnetic evolution and magnetic helicity in the solar atmosphere

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Abstract Solar atmosphere is a single system unified by the presence of large-scale magnetic fields. Topological changes in magnetic fields that occur in one place may have consequences for coronal heating and eruptions for other, even remote locations. Coronal magnetic fields also play role in transport of magnetic helicity from Sun’s subphotosphere/upper convection zone to the interplanetary space. We discuss observational evidence pertinent to some aspects of the solar corona being a global interconnected system, i.e., large-scale coronal heating due to new flux emergence, eruption of chromospheric filament resulting from changes in magnetic topology triggered by new flux emergence, sunspots rotation as manifestation of transport of helicity through the photosphere, and potential consequences of re-distribution of energy from solar luminosity to the dynamo for solar cycle variations of solar irradiance.

1 Introduction

Solar atmosphere is not simply a collection of individual features. It is a single system unified by the presence of large-scale magnetic fields. As magnetic field emerges through the photosphere into the corona, it expands significantly forming a canopy of relatively strong magnetic fields overlying field-free or weaker field areas. X-ray and EUV images show a “network” of loops interconnecting neighboring and distant active regions even across the solar equator (e.g., Tadesse et al., 2011; Pevtsov 2000). In some respect, at any given moment the solar corona is completely filled by the magnetic fields at different scales and field strengths. Because of $\nabla \times \mathbf{B} = 0$ condition, there are no “free” magnetic polarities: every magnetic “pole” is connected to somewhere else. Still, observations show that shortly after its emer-
gence, new magnetic flux establishes new connections with its neighbours, which implies that other previously existed connections would inevitably change. Thus, a seemingly localized flux emergence may lead to readjusting magnetic topology over much larger area, potentially causing additional heating and/or destabilizing distant coronal flux systems. Due to page limitations, this article is restricted to a discussion of effects of (localized) change in magnetic topology on coronal heating and remote triggering of eruptions. In addition, we also discuss the nature of sunspot rotation as possible indication of transport of helicity from below the photosphere and present consideration of the role of energy diverted to operate the solar dynamo in the total solar irradiance variations.

2 Enhanced coronal heating in response to a remote emergence of a new flux

A simple look at solar images taken in EUV or X-ray wavelength bands leaves no doubt that magnetic fields are present almost everywhere in the corona. By its nature, the coronal fields maintain a constant dynamic equilibrium: changes in magnetic connectivity in one part of the corona, may lead to changes in other parts. When a new magnetic flux emerges through the photosphere, it does not emerge in magnetically empty corona; its magnetic field will interact with pre-existing large-scale field. On smaller spatial scales, such interaction may transfer flux between closed and open fields, leading to formation of coronal jets (Moreno-Insertis et al. 2008) or coronal bright points (Kankelborg and Longcope, 1999). If a new active region develops underneath a large scale magnetic field, the coronal flux system will re-adjust to accommodate the new flux. This re-adjustment may include development of new connections (for example, see Figure 6 in Longcope 2004 showing a new loop developing between emerging active region AR9574 and existing active region AR9570, and Figure 4 in Pevtsov 2000 showing development of transequatorial loops between emerging and pre-existing active regions). Moore et al. (2002) observed episodic increase in brightness of coronal loops in the vicinity of a new flux emergence site, and have contributed these variations to the reconnection events associated with interaction between the emerging and existing magnetic flux systems. Pevtsov & Acton (2001) reported increase in brightness of solar corona over a large fraction of solar disk, associated with the emergence of a single active region. Shibata et al. (1991) have suggested that the reconnection between emerging and pre-existing magnetic systems may result in heating of large-scale corona above the emerging flux. More realistic reconnection in 3D geometry also shows formation of area of enhanced heating above the emerging flux (Galsgaard et al. 2005). Pevtsov and Kazachenko (2004) studied the emerging active region AR 8131 and its interaction with the existing region AR8132. They found a significant increase in brightness of solar corona in areas adjacent to the emerging flux even though there was no corresponding change in magnetic flux in the same area in the photosphere. Thus, for example, Yohkoh soft X-ray images showed about 485% increase
in X-ray intensity over the area encompassing two active regions, but excluding the emerging flux region itself (Figure 1). The change occurred over the 8 hours time interval. Change in the photospheric flux over the same area and same time interval was about 8%. Pevtsov & Kazachenko (2004) have estimated the total amount of thermal energy deposited in the corona as the result of interaction between the emerging and existing flux systems (but excluding the coronal loops directly associated with the emerging flux) as $2.4 \times 10^{30}$ erg. The rate of total thermal energy was found to be nearly constant during the early stages of emergence of the active region, which suggests a continuous heating.

![Fig. 1 X-ray images of ARs 8131 and 8132 taken by SXT on Yohkoh with Al.1 filter on 11 January 1998, 16:08:01 UT (panels a and c), and 12 January 1998, 00:12:55 UT (panels b and d). In lower panels, the area of brightest corona is masked to demonstrate the increase of brightness in extended area surrounding emerging active region. Adopted from Pevtsov and Kazachenko (2004).](image)

3 Changes in large-scale magnetic connectivity and eruption of a filament from a distant location

New flux emergence is often considered as a potential trigger for coronal mass ejections (CMEs), filament eruptions, and flares (e.g., Chen and Shibata 2000). Past
Fig. 2 Magnetic field lines of filament arcade, mature active region (AR10830), and emerging region AR10831 from PFSS model (upper panel). Lower panel shows quiescent filament on different stages of its evolution on June 9-11, 2003. Rapid rise of central part of filament prior to its eruption can be seen on a panel corresponding to June 11 at 18:04 UT. Magnetic field of emerging AR reconnects with mature AR, which in its turn, “steals” field lines from magnetic arcade above the filament.

statistical studies found that as much as two-thirds (Bruzek 1952) to three-fourths (Feynman and Martin 1995) of quiescent filaments were de-stabilized by the birth of a nearby active region. Wang and Sheeley (1999) used potential field solar surface (PFSS) model to demonstrate that a newly-emerged magnetic flux may reconnect with the magnetic fields of arcades overlying chromospheric filament. Weakening the arcade may destabilize the filament and lead to its eruption. However, the connectivity change may be indirect and more complex. Balasubramaniam et al. (2011) have presented case when a filament eruption was the result of multi-step reconnection. First, a newly-formed active region 10381 had developed new magnetic connectivity with existing region 10380. This new connectivity disrupted the previously existing connections between two fluxes of opposite polarity comprising AR 10380, which, in its turn, led to establishing new magnetic connections between AR 10830 and neighbouring magnetic fluxes. The latter reconfiguration weakened the magnetic arcade above the filament channel next to AR 10830 and resulted in a filament eruption. Figure 2 shows overall magnetic topology (based on PFSS model extrapolated from SOHO/MDI magnetograms) and evolution of filament as observed by the ISOON Hα telescope (Balasubramaniam and Pevtsov 2011).

4 Sunspot Rotational Motions as Indication of Helicity Transport

Sunspot rotational motions, when a sunspot exhibits a clockwise/counter-clockwise (CW/CCW) rotation relative to its geometric center, have been first reported more than a century ago (Kempf, 1910). Later studies by several researchers (e.g.,
Gnevysheva, 1941; Miller, 1971; Gopasyuk, 1981; Kucera, 1982; Solov’ev, 1984; Pevtsov & Sattarov, 1985; Nagovitsyna & Nagovitsyn, 1986) established typical properties of sunspot rotation including their average angular rotation rate (17 ± 15 deg day$^{-1}$, e.g., Pevtsov & Sattarov, 1985). In bipolar active regions, sunspots of leading and following polarity were observed to rotate in phase either in the same or opposite direction (see Figure 1 in Pevtsov & Sattarov 1985). Some sunspots exhibited change in the direction of their rotation, which was doubted “torsional oscillations of sunspots” (e.g., Gopasyuk, 1981; Solov’ev, 1984; Pevtsov & Sattarov, 1985). The periods of the torsional oscillations were found to be of on order of a few days, although much shorter periods (of a few hours) had also been reported (e.g., Druzhinin et al., 1993). Some sunspots exhibited torsional oscillations with decreasing or increasing amplitude (e.g., Kucera, 1982; Pevtsov & Sattarov, 1985).

Amplitude of sunspot torsional oscillations was found to show a solar cycle dependency (Khutsishvili et al., 1998). Torsional oscillations of sunspots were used to estimate the depth to which sunspot rotational motions penetrate below the photosphere (10,000 km – Solov’ev, 1984; and 7,500 km – Pevtsov & Sattarov, 1985, accordingly). Renewed interest in sunspot rotational motions came with high-cadence data from TRACE (e.g., Brown et al 2003).

It has been suggested that sunspot rotational motions may be an indication of helicity (twist) transport across the photosphere. According to one scenario, sunspot rotation may "pump" helicity to the corona leading to flares and CMEs. Numerical estimates indicate that the amount of helicity transported by a typical rotating sunspot is in agreement with the amount of helicity ejected by CME (e.g., Tian & Alexander 2006). Kinetic energy of sunspot rotation is about $10^{31}$ erg (Pevtsov & Sattarov, 1985), which is comparable to energy of a typical flare.

Alternatively, one can hypothesize that sunspot rotation is a response to a removal of magnetic twist (helicity) from the corona by flare or CME (e.g., Pevtsov 2008). In this latter scenario, subphotospheric portion of magnetic flux tube serves as a reservoir of helicity for the coronal portion. Prior to eruption, both parts are in equilibrium, but removing helicity from the corona disturbs the equilibrium and causes helicity to be transported from below the photosphere until a new equilibrium is established. Such evolution of twist (helicity) is observed in emerging active regions (e.g., Pevtsov et al., 2003). Active regions with strong kinetic helicity below the surface are found to be more flare productive (Reinard et al., 2010).

These two scenarios can be distinguished by the timing of sunspot rotation and flare/CME eruption. If the rotating sunspot twists the coronal magnetic field, the flares should occur at/near the maximum of twist (i.e., when the sunspot rotation is strong). If the rotation starts after a flare/CME eruption, this might indicate that it is a response to helicity removal from the corona (our second scenario). Figure 3 shows that a period with several large flares in NOAA AR9236 is followed by increase in amplitude of sunspot rotation in this active region. This seems to be in agreement with our hypothesis that sunspot rotation is a response of magnetic field on helicity removal from the corona. However, to verify the commonality of such scenario requires study of additional cases of sunspot rotation. It is worth noticing that the direction of sunspot rotation maybe hemisphere dependent. In a recent
study, R. Nightingale (private communication) had found that about 70% of rotating sunspots show counter-clockwise rotation in Northern hemisphere. For the Southern hemisphere the asymmetry is weaker, with about 56% of sunspots rotating in clockwise direction. About 15% of sunspots in both hemispheres had shown change in the direction of rotation (earlier referred to as torsional oscillations of sunspots). The hemispheric preference in rotation of sunspots is in agreement with well-known hemispheric helicity rule (Pevtsov et al., 1995), which provides an indirect support for our second scenario (sunspot rotation as transport of helicity).

Fig. 3 Rate of sunspot rotation (a) and flare activity (b) of active region NOAA AR9236. Maximum X-ray flare flux and total duration of flares are shown on panel (b). Panel (a) is courtesy of R. Nightingale.
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5 Solar Dynamo and Luminosity

Magnetic field on the Sun is generated by the processes collectively called solar dynamo. In a nutshell, motions of highly conductive plasma in presence of seed magnetic field creates electromotive effect that further amplifies magnetic field. Energy that drives these flows comes from nuclear reaction in the core of the Sun – same source that powers total solar luminosity. Thus, this energy spent on generation of magnetic field is taken out of energy going to luminosity. If there is no phase-shift between the production of the magnetic field in the convection zone and its emergence through the photosphere, bulk of magnetic field should be generated at/near solar maximum. Therefore, one can expect a dip in solar luminosity when the dynamo operation is at its maximum because more energy is diverted to the dynamo action. How significant is the effect? Rempel (2008) has estimated that the total energy of magnetic fields ($E_m$) stored at the base of the convection zone over 10 year solar cycle is about $E_m \approx 10^{38} - 10^{39}$ erg. In comparison, total thermal energy emitted by Sun over same period is $3.9 \times 10^{33}$ erg $\cdot$ s$^{-1} \times 10$ years $\approx 10^{42}$ erg or $E_L \approx 10^{41}$ erg per year.

Assuming that during solar maximum dynamo produces 10 times more magnetic field as compared with solar minimum, one can arrive to two estimates of magnetic energy produced in solar minimum and maximum: $E_M$ (minimum) = $1.5 \times 10^{37}$ erg and $E_M$ (maximum) = $1.5 \times 10^{38}$ erg. By comparison with total radiative energy of the Sun, magnetic energy is only about 0.03% in solar minimum, and it reaches 0.15% in solar maximum. Although the magnetic energy makes such a small fraction of radiative energy, it is comparable in amplitude with cycle variation of total solar irradiance and may need to be taken into consideration.

Of course, this decrease in solar luminosity due to dynamo action is in anti-phase with cycle variation of TSI. However, if this expected decrease in luminosity is real, potentially it may offset even larger variations in TSI than have been observed.

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