Homologous Flaring Activity over a Sunspot Light Bridge in an Emerging Active Region

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Abstract

Sunspot light bridges are known to exhibit a variety of dynamic and persistent phenomena such as surges, small-scale jets, etc., in the chromosphere and transition region. While it has generally been proposed that magnetic reconnection is responsible for this small-scale dynamism, persistent flaring activity lasting several hours from the same spatial location on a sunspot light bridge has rarely been reported. We combine observations from the Atmospheric Imaging Assembly and the Helioseismic Magnetic Imager on board the Solar Dynamics Observatory to investigate homologous flaring activity over a small sunspot light bridge in an emerging flux region. The homologous flares all produced broad, collimated jets including a B.6 class flare. The jets rise at a speed of about 200 km s\(^{-1}\), reach projected heights of about 98 Mm, and emerge from the same spatial location for nearly 14 hrs, after which they cease completely. A nonlinear force-free extrapolation of the photospheric magnetic field shows a low-lying flux rope connecting the light bridge to a remote opposite-polarity network. The persistent flares occur as a result of the rapid horizontal motion of the leading sunspot that causes the relatively vertical magnetic fields in the adjacent umbra to reconnect with the low-lying flux rope in the light bridge. Our results indicate that the flaring ceases once the flux rope has lost sufficient twist through repeated reconnections.

Unified Astronomy Thesaurus concepts: Sunspots (1653); Solar magnetic flux emergence (2000); Solar flares (1496); Solar magnetic reconnection (1504); Solar chromosphere (1479); Solar corona (1483)

Supporting material: animation

1. Introduction

Sunspots and pores often comprise bright structures called light bridges (LBs) that divide the umbra into two or several smaller umbral cores. LBs are either manifestations of large-scale magnetoconvection (Rimmele 2008; Rouppe van der Voort et al. 2010; Toriumi et al. 2015) or field-free regions of hot plasma in the “gappy” umbral magnetic field (Parker 1979; Choudhuri 1986; Spruit & Scharmer 2006). As a consequence, LBs are often seen along fractures where sunspots coalesce or disintegrate (García De La Rosa 1987; Schlichenmaier et al. 2010; Louis et al. 2012).

The disruption of the umbral magnetic field by the LB forces the adjacent umbral magnetic field to form a canopy (Jurčák et al. 2006), which has been suggested to facilitate magnetic reconnection in the form of several transient phenomena in the chromosphere and transition region. These include surges (Roy 1973; Asai et al. 2001; Toriumi et al. 2015; Robustini et al. 2016), strong arc-like or extended brightenings (Louis et al. 2008, 2009; Shimizu et al. 2009), reconnection jets (Louis et al. 2014a; Louis 2016; Bhat et al. 2017; Tian et al. 2018; Bai et al. 2019), small-scale transient brightenings that excite chromospheric oscillations in the adjacent umbra (Song et al. 2017a), chromospheric shocks (Song et al. 2017b; Yang et al. 2019), and oscillatory surge-like phenomena (Hou et al. 2017; Zhang et al. 2017).

The small-scale jets originating from LBs reported so far exhibited characteristic plasma temperatures below 0.1 MK (Robustini et al. 2016; Tian et al. 2018) and the general notion is that the jets occur as a result of magnetic reconnection between the overlying umbral field with either emerging bipoles in the LB or with the twisted flux tube comprising the LB (Shimizu et al. 2009). However this is at odds with most spectropolarimetric observations with exceptions as seen in Louis (2015). Louis et al. (2015a) reported the emergence of a small-scale, flat Ω-loop in a LB. However, this loop only produced a temperature excess of about 700 K in the chromosphere with close to nonzero velocities when it encountered the overlying umbral field, thus ruling out magnetic reconnection arising from the emergence. The information provided by the photospheric magnetic field does not unambiguously explain how, and if, magnetic reconnection in the LB can produce the recurrent, small-scale phenomena seen in the chromosphere and transition region.

In this article we study the homologous flaring activity in a sunspot LB during the early emerging phase of active region (AR) NOAA 11515, which involved the splitting of the main sunspot of the AR. These strong large-scale homologous flares in an LB, which include a B.6.4 flare (SOL2012-07-01T01:27), are observed rarely and we provide explanations for this particular activity pattern, based on coronal field modeling, for the first time here.

2. Observations and Analysis

2.1. Data

We use data products from the Helioseismic and Magnetic Imager (HMI; Schou et al. 2012) and the Atmospheric Imaging Assembly (AlA; Lemen et al. 2012) on board the Solar Dynamics Observatory (SDO; Pesnell et al. 2012) to study the time evolution of NOAA AR 11515 from 2012 June 30, 20:00 UT to 2012 July 2, 00:00 UT. The HMI continuum images and Dopplergrams have a cadence of 45 s. The AIA data comprise images in the 1700 Å, 304 Å, 171 Å, and 94 Å channels with a 5 minute cadence. Projection effects are assumed to be negligible as the heliocentric angle of the AR was about 33°.

In order to study the three-dimensional (3D) coronal magnetic field in and around AR 11515, we use HMLSHARP CEA_7208 data which provides the cylindrical equal area (CEA) projected photospheric magnetic field vector within automatically identified
AR patches (Bobra et al. 2014) with the azimuthal component of the vector magnetic field being disambiguated (Metcalf 1994; Leka et al. 2009). We use the full-resolution CEA data (pixel scale \(\approx 360\) km at the disk center) at 2012 July 1, 01:36 UT and 17:00 UT as input to a nonlinear force-free (NLFF) method (see Section 2.2).

2.2. Modeling

In order to perform the NLFF modeling, we apply the method of Wiegelmann et al. (2012), i.e., we combine the improved optimization scheme of Wiegelmann & Inhester (2010) and a multiscale approach (Wiegelmann 2008) to the preprocessed vector magnetic field data. The latter is achieved by applying the preprocessing method of Wiegelmann et al. (2006) to the original vector magnetic field data. For both preprocessing and optimization, standard model parameter choices, as suggested in Wiegelmann et al. 2012, have been used. We adopted a computational domain of \(544 \times 336 \times 432\) pixel\(^3\), with the photospheric magnetic flux on the lower boundary (at \(z = 0\)) being balanced to within \(\sim 10\%\).

Successful NLFF modeling is expected to deliver a 3D corona-like model magnetic field with a vanishing Lorentz force and divergence. In order to quantify the force-free consistency we use the current-weighted angle between the modeled magnetic field and electric current density (Schrijver et al. 2006) and find characteristic values of \(\sim 10^\circ\). In order to quantify the divergence-free consistency of our NLFF solutions we compute the fractional flux metric as introduced by Wheatland et al. (2000) and find values of \(\sim 1.5 \times 10^{-4}\).

3. Results

3.1. Homologous Flaring Activity

During its early phase of emergence and evolution, between July 1 and July 2, the leading sunspot of AR 11515 rapidly split into two nearly equal halves with the front half separating from its rear twin. The M5.6 (SOL2012-07-02T10:43) and C8.3 (SOL2012-07-01T15:41) flare/coronal mass ejection (CME) events associated with the splitting of the sunspot have been studied in detail by Louis et al. (2014b) and Louis et al. (2015b), respectively. In our work, we present a detailed analysis of the homologous flaring activity on 2012 July 1 that originated from a small LB located in the leading positive-polarity sunspot prior to the splitting.

Figure 1(a) shows the coronal emission in the AR on 2012 July 1 at 01:30 UT, when a B6.4 flare originated from a thin LB (location marked by a black cross) that divided the main sunspot into two umbral cores. The related emission is observed in the form of a rather broad collimated jet, in the absence of classical flare ribbon emission (for a corresponding observation see, e.g., Berger & Berdyugina 2003). The base of the jet coincides with the location of the LB. Discrete blobs are seen in the 1700 Å image at the base and mid-section of the jet (black arrows). A color composite image (panel (d)) shows that the central section in the lower half of the jet comprises plasma at coronal temperatures while the upper half exhibits chromospheric/transition region temperatures.

Figure 1(e) shows the normalized mean intensity at the characteristic chromospheric and transition region (AlA 304 Å; \(< 0.05\) MK) as well as coronal (AlA 94 Å; \(\sim 6\) MK) temperatures, computed for all pixels within a contour outlining the maximal extent of the B6.4 flare related emission. There were as many as 14 flaring events between June 30 20:00 UT and July 1 10:00 UT that were observationally verified, with the B6.4 flare being the strongest event. The flare activity in the LB ceased after around 12:00 UT on July 1.

Figure 2 shows the morphology of selected flares emanating from the LB. From the time series of observations an untwisting motion is recognized, with the plasma descending along similar trajectories during the individual events. The plasma comprising the jet moves outwards with a maximum projected speed of about 200 km s\(^{-1}\) with the cool plasma being ejected to a projected height of about 98 Mm from the base of the jet. These representative values were estimated from the 304 Å channel, using a spacetime map along a parabolic cut outlining the ejection for Event 9 at 07:16 UT.

The homologous flaring activity described above is seen in all the AlA channels, including the 94 Å channel. The events are also detected in the Geostationary Operational Environmental Satellites (GOES) X-ray flux curve, at least for the B6.3 class flare, while the majority of other events are weaker, B-class flares (comparing the relative intensity in the 94 Å channel of the B6.3 flare). In comparison, the small-scale jets/surges reported previously in LBs are confined to the lower chromosphere of the transition region, where their temperatures do not exceed 0.1 MK, and clearly lack the intense emission associated with the flares (Figures 1 and 2). Additionally, the spatial scales of the flares are far larger than those of small-scale jets/surges which are typically ejected to 10–15 Mm. These characteristics make the flares in the LB distinct from the recurrent jets and surges reported previously.

3.2. Photospheric Magnetic Field Configuration

Figure 3 shows the photospheric structure of AR 11515 at 01:12 UT (top row). The field strength in the umbral cores on either side of the LB is about 2 kG while the average and minimum field strength in the LB is about 1.2 kG and 1.0 kG, respectively. The field inclination is about 60–70° in the LB and about 80° in the penumbra. However at HMI’s spatial resolution we do not see any indication of the field changing polarity either in the LB or in the penumbral filament extending into the LB (panel (d)).

The bottom panels of Figure 3 show the leading sunspot at two different instances of time on 2012 July 1: before the B6.4 flare at 01:12 UT (panels (e)–(g)) and after the jet/flaring activity ceased at 17:00 UT (panels (h)–(j)). Evidently, by 17:00 UT the LB has become more diffuse and the penetration of the highly inclined field, associated with the LB, into the umbra has receded significantly. The area and hence the magnetic flux of the smaller umbral core east of the LB (orange contour), also reduces by 75%, from \(1.5 \times 10^{20}\) Mx to \(3.6 \times 10^{19}\) Mx. In comparison, the flux of the larger umbral core only reduces by about 5%.

The LB as well as the associated penumbral sector harbor redshifts of up to 550 m s\(^{-1}\) at 01:12 UT, which become considerably smaller at 17:00 UT. A comparison of Figures 3(f) and (i) show signatures of flux cancellation at the edge of the moat, north of the main sunspot possibly due to the relative motion of the leading sunspot in a northwesterly direction.

3.3. Coronal Magnetic Field Configuration

The NLFF modeling of the 3D coronal magnetic field on July 1 at 01:36 UT is shown in Figure 4. A system of low-lying twisted magnetic field (likely comprising a magnetic flux rope,
and so-called hereafter) connects the LB (outlined by the dashed rectangle centered around \((x, y) = (28, 21) \) Mm) to the negative-polarity moat area (see dashed outline centered around \((x, y) = (15, 38) \) Mm and the black arrow in Figure 3(f)). The particular field lines shown have been selected based on their inherent twist, with a twist of more than 0.35 turns (see Section 3.4), and which are rooted with one of their footpoints within the LB or moat area. The field lines extending beyond the field of view suggest the presence of bald batches, i.e., locations where the field overlying a polarity inversion line is parallel to the photosphere (see, e.g., Titov et al. 1993). The apexes of the twisted field lines reach coronal heights up to \(~5\) Mm (Figure 4(b)).

Visual comparison to the AIA 304 Å image, taken near-simultaneously (color-coded background in Figure 4(a)), evidences the realistic approximation of the solar corona by the employed NLFF modeling. We find that the direction of the jet feature coincides spatially between the LB and moat areas and the extension of the jet feature to the northeast of the AR is also well recovered by the field lines associated with the bald patches.

3.4. Time Evolution of Magnetic Twist

We perform an analysis of the inherent magnetic twist (thus self-helicity) of the system of twisted field lines shown in Figure 4, at 01:36 UT and 17:00 UT. We consider field lines

Figure 1. B6.4 flare in the leading sunspot of NOAA AR 11515. Panels (a), (b), and (c) correspond to AIA 94 Å, 171 Å, and 1700 Å channels, respectively. Panel (d) is a color composite image made from the AIA 304 Å (red), 94 Å (green), and 171 Å (blue) channels. The black plus symbol indicates the base of the jet on the LB. Panel (e) shows the light curve extracted from the mean intensity within the contour outlining the jet. Black and red curves correspond to the AIA 304 Å and 94 Å channels, respectively. The inset shows the AIA light curve around the time of the B6.4 flare.
that are rooted within the LB or moat area (dashed outlines in Figure 4) with at least one of their footpoints, and which emerge from locations where $|B_z| > 100$ G at the NLFF lower boundary. Based on these criteria, we compute 167 (104) field lines at 01:36 UT (17:00 UT).

Subsequently, we estimate the twist for all computed field lines as $T_\pi = \pi L/4\pi$, where $\bar{\pi}$ is the mean value of $\alpha$ at both footpoints and $L$ is the arc length of each considered field line (e.g., Leamon et al. 2003). We restrict ourselves to estimate $T_\pi$ for all field lines that are rooted at locations for which $|\pi| \gtrsim 0.1$ Mm$^{-1}$. We set the threshold on $\alpha$ in order to avoid that the twist estimation is not dominated by the many existing small-scale field lines. This reduces the number of analyzed field lines to 74 (16) at 01:36 UT (17:00 UT). The footpoints of these remaining field lines are indicated by gray triangles (positive twist) and squares (negative twist) in Figure 5. The force-free parameter $\alpha = \mu_0 J_z/B_z$, where $J_z$ is the vertical component of the electric current density, is displayed by the color-coded background in Figure 5.

We find that at 01:36 UT the majority of the considered field lines rooted in the LB and moat areas are linked to locations of negative $\alpha$, and consequently adhere to a negative twist (see inset at top right corner of Figure 5(a)). The distribution of $T_\pi$ as a function of $L$ (bottom right inset) shows that the negative twist is characteristic for both shorter and longer field lines. From the considered field lines we find a median value of $\langle T_\pi \rangle = -0.2 \pm 0.1$. Note that the number of considered field lines is greatly reduced, by a factor of nearly five, as many of the field lines rooted in the selected subfields correspond to a value of $|\pi| < 0.1$ Mm$^{-1}$, based on the criterion described above.

These results suggest that the flux rope connecting the LB and moat area lost a considerable amount of twist, as the number of field lines with a twist $\gtrsim 0.1$ at 01:36 UT reduced significantly at 17:00 UT, likely due to the repeated reconnection events.

4. Discussion

The homologous flaring activity in the sunspot LB lasts for at least 14 hrs with the strongest event being a B6.4 flare (see Figure 2). In the present case, only the 3D NLFF reconstruction of the coronal magnetic field reveals the importance of temporal changes within specific photospheric areas of the AR, such as the moat region located to the northeast of the main sunspot (see Figure 4). In particular, it is connected by a low-lying magnetic flux rope to the LB, spatially associated to the observed flare events.

The chief driver for the recurrent flares originating from the LB is the horizontal motion of the leading sunspot in a northwesterly direction. Consequently the more vertically oriented magnetic fields in the adjacent sunspot umbra to the east of the LB may reconnect with the highly inclined fields at the leg of the flux rope, producing the observed collimated jet emission (top panel of Figure 4). During the several subsequent, homologous reconnection events the twist of the flux rope is liberated (Figure 5), resulting in a weakly
Figure 3. Top: continuum image (left) and vertical magnetic field (right) on 2012 July 1 at 01:12 UT. Middle: enlarged field of view (indicated by the black box in panel (a)) of the LB in the eastern part of the leading sunspot. Panel (c) corresponds to the horizontal magnetic field, shown with white arrows for every second pixel. Panels (e)–(g) correspond to the continuum intensity, vertical component of the magnetic field, and line-of-sight velocity at 01:12 UT. Panels (h)–(j) are the same as those on the left but at 17:00 UT. The magenta contours indicate redshifts of 550 m s$^{-1}$ and the black arrows point to a network flux patch. The thick black circle encloses the LB. The dotted black contours outline the sunspot boundary, while the orange and black solid contours denote the smaller and larger umbral cores, respectively.
twisted/sheared field arcade no longer conducive to magnetic reconnection. Additionally, flux cancellation at the remote leg of the flux rope in the moat area could facilitate reconnection in the rope, and the flaring ceases as the footpoint diffuses. The reduction of photospheric magnetic flux at/close to the regions where the eruptions ensue is generally consistent with observations and magnetohydrodynamic simulations (Forbes et al. 2006, and references therein).

The line-of-sight velocity in the LB and its surroundings is dominantly redshifted (Figure 3(g)). If the homologous nature of the flares were the result of small-scale loops emerging in the LB and reconnecting with the overlying umbral field (Tian et al. 2018), one would expect blueshifts either in localized patches or along the body of the LB (Louis et al. 2020). With HMI’s native spatial resolution of \(~320\) km, we do not find evidence for opposite-polarity fields above uncertainties within the LB, though we do not exclude the possibility of small-scale velocity and magnetic inhomogeneities having been present (Louis et al. 2009, 2015a; Louis 2015).

It has been known that LBs can be associated with the large-scale magnetic configuration of an AR. Observations by Berger & Berdyugina (2003) describe a set of flare ribbons extending along the LB as a result of magnetic reconnection in the corona. However, the C2.0 flare was the only event that occurred in the AR on that day. Guo et al. (2010) reported recurrent surges in Hα from an LB which triggered a filament eruption and an associated M2.5 flare. However, the lack of vector magnetic field data does not account for the persistent nature of the surges or the topological association of the filament to the LB. The homologous flaring activity in a sunspot LB, described in this article, is observed unambiguously in all AIA channels and is strongly supported by our models of the coronal magnetic field, which, to the best of our knowledge, has not been reported previously.
5. Conclusions

The presence of small-scale chromospheric and coronal transients such as surges, jets, etc., in sunspot LBs has generally been attributed to magnetic reconnection but the processes, rendering these transients homologous, are poorly understood. Homologous flares in LBs can be considered extremely unique and rare, as they are an irrefutable evidence of magnetic reconnection occurring within the strong field domain of sunspots. In this article, we describe a series of intermittent flares in a sunspot LB. The leading sunspot exhibits a rapid horizontal motion consequently splitting into two nearly equal halves. Our coronal magnetic field models show a low-lying twisted flux rope connecting the LB to the moat area of the sunspot. The proper motion of the sunspot causes the umbral magnetic fields to reconnect with the low-lying flux rope, producing the flares, with the collimated jets perfectly aligned along the flux rope’s axis. The repeated reconnections render a considerable loss of twist in the flux rope which is substantiated by our extrapolations. The combined effect of the above renders the flux rope to return to a more relaxed state whereby the flaring activity ceases. The uniqueness of the observations and the coronal magnetic field models provide new insight into the recurrent nature of flares in an LB.

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Figure 5. Force-free $\alpha$ and twist parameter $T_{\alpha}$ within NOAA 11515 at (a) 01:36 UT and (b) 17:00 UT on 2012 July 1. Dashed outlines to the northeast ($x, y = 15.38$ Mm) and southwest ($x, y = 28.21$ Mm) outline the moat area and LB, respectively, from which field lines were computed. Footpoint locations of all considered field lines adhering to positive (negative) $T_{\alpha}$ are marked by gray triangles (squares). The color-coded background shows the force-free parameter $\alpha$, scaled to $\pm 1$ Mm$^{-1}$. Black (gray) contours outline $B_z$ of 1000 ($-200$) G. The insets show the twist of the field lines as a function of $\alpha$ (top right corners) and as a function of the lengths of the field lines (bottom right corners).
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Louis & Thalmann