The Formation of an Atypical Sunspot Light Bridge as a Result of Large-scale Flux Emergence

Rohan E. Louis1, Christian Beck2, and Debi P. Choudhary3

1 Udaipur Solar Observatory, Physical Research Laboratory, Dewali Badi Road, Udaipur—313001, Rajasthan, India; rlouis@prl.res.in
2 National Solar Observatory (NSO), 3665 Discovery Drive, Boulder, CO 80303, USA
3 Department of Physics and Astronomy, California State University, Northridge (CSUN), CA 91330-8268, USA

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Abstract

We use a combination of full-disk data from the Solar Dynamics Observatory and high-resolution data from the Dunn Solar Telescope (DST) to study the formation, structure, and evolution of an atypical light bridge (LB) in a regular sunspot. The LB results from the emergence of magnetic flux with one footpoint rooted in a pore outside the parent sunspot that appears about 17 hr before the LB. The pore has a polarity opposite to that of the sunspot and recedes from it at a speed of about 0.4 km s\(^{-1}\). This is accompanied by the development of an elongated magnetic channel in the outer penumbra that triggers the formation of the LB when it reaches the inner penumbral boundary. The LB is a nearly horizontal structure with a field strength of about 1.2 kG that exhibits long-lived photospheric blueshifts of about 0.85 km s\(^{-1}\) along its entire length. The emergence of the LB leads to dynamic surges in the chromosphere and transition region about 13 minutes later. We derive the photospheric and chromospheric structure of the LB in the DST data from spectral line parameters and inversions of He I at 1083 nm, Si I at 1082.7 nm, Ca II IR at 854 nm, and H\(_\alpha\) at 656 nm and speckle-reconstructed imaging at 700 and 430 nm. The LB shows an elongated filamentary shape in the photosphere without lateral extrusions. The thermal inversion of Ca II IR reveals the LB to be about 600–800 K hotter than the umbra. Different sections of the LB are elevated to heights between 400 and 700 km. Our results indicate that LB formation is part of a flux emergence event with the LB envelope reaching a height of about 29 Mm before dissolving after about 13 hr. We conclude that the existence of persistent, large-scale photospheric blueshifts in LBs is the most likely criterion for distinguishing between flux emergence events and overturning convection in field-free umbral intrusions.

Unified Astronomy Thesaurus concepts: Sunspots (1653); Solar magnetic flux emergence (2000); Solar magnetic fields (1503); Solar photosphere (1518); Solar chromosphere (1479); Solar corona (1483)

Supporting material: animation

1. Introduction

Sunspots are the strongest and largest concentrations of the magnetic field in the solar photosphere (Solanki 2003). During their lifetime, the umbral core often comprises one or more elongated, bright structures called light bridges (LBs). LBs are usually present during the early stages of sunspot formation (Schlichenmaier et al. 2010) or the late stages of sunspot decay (Garcia de La Rosa 1987) and can have an umbral, penumbral, or granular morphology depending on their evolutionary epoch (Muller 1979; Katsukawa et al. 2007; Louis et al. 2012). High-resolution observations of granular LBs typically show a dark lane running along their central axis (Sobotka et al. 1994; Berger & Berdyugina 2003; Lites et al. 2004; Lagg et al. 2014), while penumbral LBs exhibit small-scale bars near the edges of the filamentary structure (Louis et al. 2008; Rimmele 2008).

The magnetic field in LBs is usually weaker and more inclined in comparison to the neighboring umbra (Lites et al. 1991; Rueedi et al. 1995; Leka 1997). At photospheric heights, LBs can be perceived as field-free intrusions of hot plasma into the gappy umbral magnetic field (Parker 1979; Choudhuri 1986) or as large-scale magnetocovrentive structures (Rimmele 1997, 2004). This intrusion of hot, weakly magnetized plasma forces the adjacent umbral magnetic field to form a canopy above the LB (Jurčák et al. 2006). Such a magnetic topology has been suggested to be responsible for a wide variety of transient phenomena, such as surges in H\(_\alpha\) (Roy 1973; Asai et al. 2001; Robustini et al. 2016), strong brightenings and ejections observed in Ca II H (Louis et al. 2008, 2009; Shimizu et al. 2009), small-scale jets (Louis et al. 2014a; Tian et al. 2018), and brightness enhancements in the transition region (Berger & Berdyugina 2003).

Katsukawa et al. (2007) reported that the formation of an LB is accompanied by several umbral dots (UDs; Loughhead et al. 1979; Rimmele 1997; Sobotka et al. 1997a, 1997b) emerging from the leading edges of penumbral filaments, which are seen to rapidly ingress into the umbra. Using high-resolution observations from the Solar Optical Telescope (Tsuneta et al. 2008) on board Hinode (Kosugi et al. 2007) spanning several days, they identified the precursor of LB formation to be relatively slow inward-moving UDs, which emerge well inside the umbra. They concluded that the appearance of UDs in the central part of the umbra leads to a weakening of the umbral magnetic field by hot subphotospheric plasma that facilitates the emergence of a buoyant flux tube in the form of the intruding penumbral filament that ultimately forms the LB.

The presence of an LB during the early stages of sunspot or active region (AR) formation can be attributed to weakly magnetized plasma being squeezed by the horizontal convergence of stronger emergent flux (Cheung et al. 2008, 2010). In such a case, the LB exhibits a large-scale convective upflow that continuously transports the horizontal, but mostly weaker, magnetic field to the surface. This horizontal magnetic field reconnects with the adjacent vertical umbral fields, resulting in episodic and intermittent brightenings and surge ejections.
(Toriumi et al. 2015a, 2015b). While LBs represent large-scale convective upflows, they can also be sites of small-scale magnetic flux emergence in the form of flat horizontal loops harboring a siphon flow (Louis et al. 2015). The interaction of convective flows in the LB with the strongly magnetized environment of the sunspot can produce several small-scale magnetic and plasma inhomogeneities in the former (Louis et al. 2009; Louis 2015).

In this article, we study the formation and properties of an unusual LB using satellite-based full-disk data from the Solar Dynamics Observatory (SDO) and ground-based high-resolution observations from the Dunn Solar Telescope (DST). Sections 2 and 3 describe the data used and the analysis techniques, respectively. We present our results in Section 4. A discussion and conclusions are included in Sections 5 and 6, respectively.

2. Observations

We studied the leading sunspot in NOAA AR 12002 from 2014 March 12 23:00 UT to March 14 06:20 UT. The long-term evolution of the AR was analyzed using SDO observations, while a complex instrument suite at the DST was employed to study the magnetic and thermodynamic properties of the sunspot with high resolution at a particular epoch of its evolution on March 13 at about 20:37–21:00 UT. Both data sets are described below.

2.1. SDO Data

The SDO data consisted of continuum intensity filtergrams, Dopplergrams, and the vector magnetic field from NASA’s Helioseismic Magnetic Imager (HMI; Schou et al. 2012) at a cadence of 12 minutes. The vector magnetic field products were projected and remapped to a cylindrical equal-area Cartesian coordinate system centered on the AR. In addition, we utilized similar data at a cadence of 1 hr between 13:00 UT and 23:00 UT of March 12 and from 09:12 UT to 23:00 UT of March 14. The HMI data were complemented with images from the Atmospheric Imaging Assembly (AIA; Lemen et al. 2012) at a cadence of 5 minutes in the 1700, 304, and 171 Å channels. HMI data gaps occurred between 06:12 UT and 09:12 UT on March 13 and 14. A similar data gap was also present in the AIA time series from 06:20 UT to 07:35 UT on March 13 and 14.

2.2. High-resolution DST Data

For the DST observations, we used a combination of the Interferometric BI-dimensional Spectrometer (IBIS; Cavallini 2006; Reardon & Cavallini 2008), the SPectropolarimeter for INfrared and Optical Regions (SPINOR; Socas-Navarro et al. 2006), the Universal Birefringent Filter (UBF; Beckers et al. 1975), and one more imaging camera. A sketch of the setup is shown in Figure 1. A dichroic beam splitter (BS) was used to reflect all light below 450 nm toward a G-band imager. A second, achromatic 50–50 BS split the rest of the light evenly between IBIS and SPINOR. The modulator of SPINOR, a rotating wave plate, was placed directly in front of its entrance slit. The wave plate unfortunately has a small wedge angle that causes a beam wobble with a cone angle of about 0.003 deg. With the placement as close to the slit plane as possible, the beam wobble has a diameter of about 0"14 on the Sun. The physical slit width of SPINOR of 0"22 on the Sun was therefore increased to an effective slit width of 0"36. The SPINOR slit-jaw (SJ) unit reflected light toward a second imaging channel through the UBF, which was tuned to the line core of Hα. There was no image motion of the solar image because of the double passage through the rotating modulator, but the slit plane—and hence the slit, the hairlines, and all dust particles on its surface—exhibited a circular image motion in the Hα imaging channel. In addition, spatial scanning of the solar surface for SPINOR is done by moving the slit unit. It was thus not possible to obtain a complete gain correction for the Hα SJ images.

With IBIS, we sampled the chromospheric spectral lines of Ca II IR at 854.2 nm and Hα at 656 nm in spectroscopic mode. With SPINOR, we obtained Stokes vector polarimetry of H1 at 1083 nm and Ca II at 854 nm. A third camera for observing Hα with SPINOR turned out to be not correctly synchronized to the modulator position on that day, so that only spectroscopic data were acquired. The spatial, spectral, and temporal sampling of all instruments are listed in Table 1. The seeing conditions were only medium; the data originally were only intended as a performance test of the rather complex setup.

With the setup described above, we observed the leading spot of NOAA AR 12002 on 2014 March 13, from about UT 20:37 to UT 21:00. The sunspot was located at x, y ~ 40°, −180° at a heliocentric angle of about 12°. We scanned the field of view (FOV) with SPINOR with 200 steps of 0°293 step widths with an integration time of 5 s per step. The G-band and Hα imagers were triggered by SPINOR at the start of each scan step. IBIS sequentially scanned Ca II IR 854 nm and Hα with a nonequidistant sampling of 27 wavelength points for each line and obtained 63 spectral scans of the two spectral lines between UT 20:44 and UT 20:57 at a cadence of 12 s. Table 1 lists other technical characteristics of the DST data.

3. Data Analysis

3.1. Speckle Reconstruction

We used the Kiepenheuer-Institut Speckle Interferometry Package (Wöger & von der Lühe 2008; Wöger et al. 2008) to run a speckle reconstruction of the IBIS broadband (BB) images at 700 nm, the G-band images at 430 nm, and the Hα SJ images at 656 nm. For IBIS, we combined the 54 BB images of

![Figure 1. Schematic drawing of the setup at the DST. BS 1 reflected all light below 450 nm toward a G-band imaging camera at 430 nm. The 50–50 achromatic BS 2 split the light evenly between IBIS (Hα, Ca II IR 854 nm) and SPINOR (Hα, Ca II IR 854 nm, He I 1083 nm). The light reflected by the SJ passed through the UBF, which was tuned to the line core of Hα. This beam passed twice through the rotating modulator (MOD).](image-url)
each spectral scan acquired simultaneously with the spectra into one speckle burst for a total of 63 bursts. For the latter two, we only used the last 60 of the 200 images in two speckle bursts of 30 images each. Some of the IBIS bursts got impacted by clouds, while for the Hα images the reconstruction amplified the flat-field residuals caused by the beam wobble of the modulator. We thus dropped the UBF Hα images from further analysis and maintained only the second G-band reconstruction and the three IBIS BB reconstructions of spectral scans No. 2, 38, and 61 at times of good seeing.

3.2. Line Parameters

Spectroscopy—For all intensity spectra, we determined the following quantities: the continuum or line-wing intensity, the line-core velocity of all chromospheric lines and of the photospheric Si I line at 1082.7 nm, and bisectors at either 10 or 30 equidistant line depth levels between the line core and the continuum or line wing for all chromospheric lines. We stored exposure time [ms] 100 Cadence [s] 12

Table 1

| Instrument | SPINOR | IBIS | UBF | G-band |
|------------|--------|------|------|--------|
| λ [nm]     | 1082 ± 2 | 854 ± 2 | 656 ± 1 | 854.2 ± 0.2 | 656.25 ± 0.2 | 656 ± 2 | 430 ± 2 |
| Spatial x/y [″ pixel⁻¹] | 0.36/0.561 | 0.36/0.366 | 0.36/0.359 | (0.098)² | (0.139)² | (0.085)² |
| Spectral [pm pixel⁻¹] | 9.29 | 5.85 | 4.19 | ~4–40 | … | … |
| FOV x-y [†°] | 60–110 | (90)² | (88)² | (140)² |
| Exposure time [ms] | 100 | 80 | 200 | 10 |
| Cadence [s] | … | 12 | 7 | 7 |

CAIcal Inversion based on a Spectral ARchive (CAISAR; Beck et al. 2015, 2019) code that assumes local thermodynamic equilibrium (LTE). For both the LTE and non-LTE (NLTE) version, the CAISAR code can reproduce observed spectra to a level of a few percent of Iₚ (Beck et al., 2014, 2015, 2019). We converted the rms difference of observed and best-fit spectra to the corresponding rms variation in temperatures at different optical depth levels as an error estimate (calculation courtesy of J. Jenkins; details will be published elsewhere). This yielded an rms temperature error of 1σ of about 20 K for log τ > −2, an increase from 20 to 100 K over the range −2 > log τ > −5 and of 100–150 K for −5 > log τ > −6. A comparison of LTE and NLTE results of the same spectra showed close agreement for log τ > −3 (Beck et al., 2015) and a difference in absolute temperature values by a factor of about 2 at log τ = −5. All NLTE temperatures given here were derived from the LTE results by a multiplication with the NLTE correction curve for the umbra as given in Figure 6 of Beck et al. (2015).

The spectropolarimetric Ca II IR data from SPINOR were subsequently inverted with the same simplified approach as in Beck & Choudhary (2019) assuming an exponential decay of the magnetic field with optical depth in the form of B(log τ) = B₀ · exp(−log τ/Δτ) with the free parameters B₀ and Δτ while keeping the temperature stratification fixed to the output of the prior inversion step.

4. Results

4.1. General Overview of the LB and Its Surroundings

NOAA AR 12002 transited the solar disk on 2014 March 8 to 19. During the early phase of the AR’s emergence between March 10 and 12, a large sunspot in the leading polarity developed from several umbrae within a common penumbra, while several LBs were present in both the leading and follower spots. At its fully developed state, the leading polarity of the AR comprised two sunspots, the smaller of which developed and fragmented over 48 hr between March 12 and 13. Our region of interest is an LB that appeared in the larger spot of the leading polarity of the AR when the latter was fully developed and did not exhibit a significant change in its area. The LB in the leading sunspot was transient and there were no major flares or coronal mass ejections during its lifetime.

Figure 2 shows the leading sunspot of positive polarity in NOAA AR 12002 on 2014 March 13 at 18:48 UT. There are a couple of pores (x, y: 25″, 45″) of the same polarity as the sunspot to the east of it. The penumbral region closest to these pores appears perturbed. To the southeast of the leading sunspot is a smaller set of pores of opposite polarity (x, y: 22″, 25″) that are further out from the visible sunspot boundary (panel 3). The sunspot comprises an LB, about 10″ in length, that runs along the north–south direction with its axial span.
very close to the western umbra–penumbra boundary encompassing the smaller umbral core of about 13% of the total umbral area. The LB shows photospheric blueshifts of about 0.5–0.7 km s\(^{-1}\) from its northern end to the mid-penumbra in the southern section of the sunspot (panel 2), while the outer penumbra shows redshifts of about 0.7 km s\(^{-1}\) arising from the photospheric Evershed flow (Evershed 1909). In addition a small part of the northern end of the LB harbors very weak redshifts of about 0.2 km s\(^{-1}\) (x, y: 6 0′, 5 4″) at the location where the LB meets the umbra–penumbra boundary. Panel 3 shows that the vertical component of the magnetic field in the LB is greatly reduced in comparison to the adjacent umbra, where the values are about 1700 G. In the midsection of the LB the vertical component is about 450 G at its center and about 900 G at the edges. Further down the LB, the values are even smaller, ranging between 115 and 260 G, while those in the adjacent penumbra are about 650 G.

The lower panels of Figure 2 show the LB in different AIA channels. The 1700 Å channel from the upper photosphere (panel 4) indicates that the LB is brighter than the adjacent penumbra having a higher contrast than in the HMI continuum intensity. The He II 304 Å image from the upper chromosphere (panel 5) shows that there are several surges that start from the right/western edge of the LB (x, y: 61″, 50″) and extend close to the sunspot boundary. These surges are seen all along the length of the LB and are characterized by dark filamentary structures along their length terminating in intense bright blobs. The bright blobs are also visible in the AIA 171 Å image, although the filamentary structures of the surges are more diffuse.

An animation of the temporal evolution from March 12 UT 23:00 until March 14 UT 05:40 in the same quantities as in Figure 2 is provided in the online material. The relation between the magnetic flux emergence and the LB, the evolution of bright grains and surges, and the sunspot rotation are more obvious in the animation than in the stills used for subsequent figures.

### 4.2. LB Formation

In this section, we analyze the events that led to the formation of the LB in the leading sunspot.

#### 4.2.1. Emergence of Pore

The top panels of Figure 3 show the leading sunspot at the beginning of 2014 March 13. The umbra exhibits several bright intrusions at this point of time, specifically in the central–western part. The large dashed circle (x, y: 22″, 25″) in the panels marks a region just outside the spot boundary where a diffuse dark patch is seen that coincides with weak, mixed-polarity fragments. The dotted circle (x, y: 33″, 28″) indicates a section of the outer penumbra that is involved in the magnetic flux emergence. Panel 2 of the figure shows the emergence of a negative-polarity patch in the QS, which is linearly extended in the direction of the sunspot as seen in the \(B_x\) image. The continuum intensity image also shows dark features starting from the sunspot boundary and reaching up to the...
opposite-polarity patch about 6° away. In addition, the penumbra in the dotted circle exhibits a visible brightening below a filamentary structure (continuum intensity) that is oriented in the direction of the emergent flux in the QS. The LOS velocity image in panel 2 indicates weak blueshifts of about 0.17 km s⁻¹ at the location of this brightening.

The newly emergent patch of opposite polarity in the QS comprises redshifts of about 0.75 km s⁻¹ on the side closest to the spot and blueshifts of about 0.55 km s⁻¹ on the side furthest from the spot. Nearly 2 hr later (panel 3) the opposite-polarity patch has developed into a pore that is bigger and more circular and has traversed further from the sunspot boundary. The penumbral sector closest to the emergent pore also exhibits a well-defined filamentary channel. We estimate the apparent horizontal speed of the pore, as it recedes from the sunspot, to be about 0.4 km s⁻¹ from the time of its emergence at 04:00 UT. Panels 3 and 4 of the continuum intensity also show that the conspicuous brightening in the outer penumbra progresses about 3° to the west, while the region between the sunspot boundary and the pore is filled with small-scale mixed-polarity fragments.

The pore exhibits strong redshifts of about 1.4 km s⁻¹, while the region in the penumbra marked with the dotted circle is weakly redshifted to about 0.1 km s⁻¹ and clearly stands out because the surrounding penumbra is dominated by redshifts greater than 0.5 km s⁻¹.

Figure 3. Emergence of pore in the QS just outside the leading sunspot on 2014 March 13 (large dashed circle). The left, middle, and right columns correspond to the continuum intensity, B_z, and LOS velocity, respectively. The smaller dotted circle indicates changes in the sunspot penumbra associated with the pore’s emergence.
Following the data gap between 06:12 and 09:12 UT, we find additional negative-polarity flux to have emerged close to the pore (Panel 5), which is associated with redshifts of about 1.0 km s\(^{-1}\). On the other hand, the bright patch in the outer penumbra is associated with a kink in the filamentary penumbra located at the sunspot boundary. We observe that over a duration of about 9 hr, starting at 00:00 UT on 2014 March 13, the flux of the pore increases from \(-1.7 \times 10^{18}\) to \(-1.4 \times 10^{20}\) Mx and the pore moves nearly 15” away from its point of emergence. The sunspot umbra also exhibits fewer bright intrusions as seen in Panel 1 with only one set of penumbral filaments extending into the umbra.

Figure 4 shows the horizontal magnetic field overlaid on the vertical component before and after the emergence of the pore at 00:00 UT (top) and 06:12 UT (bottom), respectively, on 2014 March 13. Arrows have been drawn for every pixel, where the field strength exceeds 200 G. An example arrow corresponding to a field strength of 1 kG is shown in the lower left corner above the timestamp.
has reduced by about 180 G. In addition to the pore, the transverse magnetic field indicates smaller loops between opposite-polarity fragments, just west and northwest of the pore. While the filamentary penumbral structure appears to be aligned in the direction of the pore, the difference between its orientation and the transverse magnetic field varies from about 15° in the mid-penumbra to about 40° in the outer penumbra.

The emergence of the pore is associated with several transient events in the chromosphere and transition region as shown in Figure 5. Jet-like ejections are seen to emanate close to the emergent pore \((x, y: 60'', 50'')\) as well as just outside the sunspot boundary. AIA 304 and 171 Å images indicate that the jets occur beneath large-scale structures connecting the leading sunspot to the following polarity of the AR. The jets are possibly associated with flux cancellation in the vicinity of the emergent pore involving small-scale parasitic magnetic patches as they encounter the moving magnetic features (MMFs) streaming from the leading sunspot. Between 02:00 UT and 06:00 UT we detect six such jets with lifetimes of about 4–5 minutes, while some of the jets, such as those shown in panel 4, last for about 20 minutes.

4.2.2. Precursor to LB Formation

As shown in panel 5 of Figure 3, a single set of penumbral filaments is seen to extend into the umbral core of the leading sunspot at a time when the pore in the QS has fully developed. Figure 6 further shows the evolution of the leading sunspot using a polar transformation of the Cartesian image shown in the top left corner of the panel. The figure shows that the single set of penumbral filaments at 09:12 UT on 2014 March 13 eventually breaks up by 12:24 UT (panel 3), which involves the filament detaching as several bright blobs or UDIs that move further into the umbra. The detachment occurs at the northern end of the intrusion and progresses southward toward the umbra–penumbra boundary with time. In addition, the kinked penumbral structure near the sunspot boundary, described in the previous section, fragments into smaller patches that move further outward closer to the pore (arrows in panels 1 to 3).

Panels 3, 4, and 5 show that while the umbra is devoid of any intrusions from the penumbra, an elongated channel develops in the penumbra extending from the sunspot boundary to the inner penumbra (ellipse in right panels). Panels 6 and 7 indicate that this channel moves further into the umbra–penumbra boundary while simultaneously a bright intrusion appears in the umbra. This intrusion develops rapidly over a duration of about 1 hr starting at 15:48 UT (panel 8) while its base coincides with a relatively broad penumbral section (plus symbol) comprising several filaments. The base of this intrusion is slightly displaced from the location of the previous intrusion (cross symbols in panels 1 and 8). The polar image of the vertical component of the magnetic field in panel 8 shows that the new umbra intrusion can be traced outward along the elongated magnetic channel in the penumbra and up to the pore in the QS (dashed line in right panels). This connection between the pore and the intrusion evidently deviates from a strictly radial alignment. The new structure that forms at 16:48 UT, 3.5 hr after the earlier intrusion, is more extended as well as long-lived and will henceforth be referred to as the LB for the remainder of the article.

Figure 7 shows a sequence of AIA images in the 171 Å channel leading up to the formation of the LB in the leading sunspot. The dotted circle in panel 1 shows a large part...
of the umbral core to be devoid of any large-scale structures. The half-S-shaped loop at the top right section of the dotted circle overlies the diffuse chain of UDs north of the penumbral intrusion (panel 1 of Figure 6). A faint footpoint of a loop, rooted in the umbra, is seen around 08:50 UT (panel 2). This footpoint appears possibly as a response to a small flare that occurs in the AR around 08:35 UT. Panel 3 shows the footpoint getting brighter, and the loop associated with the footpoint is seen to exhibit a counterclockwise rotation (white arrows; see also the animation in the online material). The umbra of the leading sunspot is now obscured by several loop footpoints as evident from the figure. The rotation of the loops is also observed in the northern sector of the sunspot (black arrows).

We estimate that the loops rotate by about 40° over a duration of about 4 hr. The red arrow in panel 6 shows the first signature of the surges emanating from the newly formed LB.

To summarize, the formation of the LB is preceded by the emergence of a pore nearly 17 hr earlier just outside the sunspot boundary. The pore has an opposite polarity to the parent sunspot and drifts away from it at a speed of about 0.4 km s⁻¹. Several jets occur in the chromosphere and transition region in close proximity to the pore. The emergence of the pore is accompanied by an elongated magnetic channel in the penumbra that eventually reaches the umbra–penumbra boundary, triggering the formation of the LB. The LB occurs close to the location where an umbral intrusion from the
penumbra existed about 3.5 hr earlier. The relation of the flux emergence to the subsequent formation of the LB is more obvious in the animation in the online material.

4.3. LB Properties from DST Observations

In this section, we describe the thermal, kinematic, and magnetic structure as derived from the DST data from multiple instruments. These results illustrate a snapshot in the long-term evolution of the LB on 2014 March 13 at about 20:50 UT and provide a 3D perspective of the LB.

4.3.1. LB Morphology: Shape in Photosphere and Chromosphere

Figure 8 shows the leading sunspot observed from the instrument suite at the DST. The speckle-reconstructed images (top four panels) indicate that the southern base of the LB at the inner penumbral boundary is devoid of any penumbral features such as dark cores or penumbral grains, although the average intensity is similar to that of the neighboring penumbra. The southern end of the LB is characterized by a couple of relatively bright filamentary structures (arrows in right panels). They resemble “reverse” penumbral filaments, with bright grains on the outer end of the penumbra and then a photospheric penumbral filament going toward the umbra in the opposite direction to the regular sunspot structure. The northern part of the LB at this point in time has developed into an S-shaped hook that terminates at the inner penumbral boundary to the west. The LB is seen as an extension of the penumbra running across the umbral core of the leading sunspot. There are no indications of dark lanes perpendicular to the long axis of the LB. There are no discernible changes over the period of 11 minutes spanned by the IBIS broadband speckle reconstructions.

Figure 7. Evolution of large-scale loops in the leading sunspot on 2014 March 13. The dotted circle shows the onset of a bright loop whose one end is rooted in the umbra. The white and black arrows indicate the motion of large-scale loops in the counterclockwise direction. The red arrow corresponds to the surge from the LB.
Figure 8. Top: Speckle-reconstructed IBIS broadband and G-band images taken from the DST on 2014 March 13. The three arrows in the right panels indicate bright grains in the outer penumbra with their corresponding filaments directed toward the umbra. Bottom: IBIS narrowband filtergrams obtained in Hα (top) and Ca II IR (bottom) at 20:51 UT on 2014 March 13 corresponding to spectral scan No. 38. The left (right) column shows the line-wing (line-core) images.
The bottom panels of Figure 8 show the spectral scans taken with IBIS in Hα and Ca II IR. In the wing of the Ca 854.2 nm line the LB exhibits a central dark lane along its axis in its middle part, as also seen in the speckle-reconstructed images, while the line-core image shows that the entire LB, from its southern end to the S-shaped hook in the north, has an enhanced intensity as compared to the rest of the sunspot. The S-shaped hook is oriented at nearly 90° to the axis of the LB and is seemingly continued by a dark fibril in the Hα line core image. The curvature in the southern end of the LB, however, is mostly radial. A similar feature is seen in the Hα line core image, although the brightness contrast is reduced. The blue line wing in Hα shows signatures of surges on the LB (Figure 2), at its southern and northern ends. In addition there are intensely bright patches on the LB.

4.3.2. Thermal Structure of LB

Figure 9 shows the Ca II IR LTE inversion results of IBIS spectral scan No. 2 at 20:44 UT on March 13. The LB stands out at all heights, both in the photosphere and in the chromosphere between log \( \tau = -2 \) and log \( \tau = -5 \), and its shape is retained in terms of height as well. The figure also shows that the LB is hotter in the chromosphere than in the rest of the sunspot. The enhancement in temperature relative to the umbral at log \( \tau = 0 \), −1, −2, −3, −4, and −5 is 452 (475) K, 385 (398) K, 402 (406) K, 595 (679) K, 774 (1036) K, and 637 (1356) K, respectively, where the numbers in parentheses correspond to the NLTE values. At log \( \tau = -3 \), −4, and −5, the maximum temperature in the LB is 4361 (4978) K, 4390 (5879) K, and 3985 (8478) K, respectively. The maximal difference relative to the umbra is 600–800 K and occurs at about log \( \tau = -3.6 \). This enhancement in temperature along the LB is seen throughout the IBIS time sequence of 15 minutes. The bright filamentary penumbra at the southern end of the LB is associated with an enhancement of 200 K for log \( \tau \geq -2.5 \) (~280 km), while it is cooler than the penumbra by about 300 K at greater heights. From log \( \tau = -2.5 \) to log \( \tau = -3.5 \) the LB is hotter than all other regions in the FOV, including the QS, by 600–800 K.

Figures 10 and 11 show 2D x–z and y–z plots of the temperature on cuts across and along the LB, respectively, for three IBIS spectral scans No. 2, 38, and 61 at \( t = 0, 7, \) and 11 minutes. These scans correspond to 20:44 UT, 20:51 UT, and 20:55 UT on March 13, respectively. The lateral width of the LB cross section is about 1–2 Mm, while the LB extends to a height of about 1 Mm. Cuts 1 and 2, which correspond to the southern end of the LB, reveal the thermal distribution across the LB to be quite complex, with the boundary enclosing the hot structure increasing in height from east to west. Cuts 3–6 show a simpler, more homogeneous thermal structure across the axis of the LB. Interestingly, these cuts also exhibit the loss of a continuous connection of the temperature enhancement to the photosphere, with the LB appearing nearly isolated at mid-chromospheric heights.

The highest temperature is usually found at the center of the structure, e.g., cut No. 2 (top row), cut No. 3 (bottom row), and cut No. 5 (top row). Proceeding from cuts 1 to 6, we find that the center of the temperature enhancement corresponding to the LB moves from the photosphere at about 400 km to the lower chromosphere at 600 km. Cuts 1 and 2 show that the LB is...
hotter in comparison to the remaining cuts at a height range of 300–700 km. In general the temperature distribution in the LB is highly inhomogeneous along and across its axis, as well as in terms of height, which can also be visualized in Figure 11. The maximum temperature along cuts 1 and 2 across the LB is about 5293 and 5075 K, while the same for cuts 3–6 is about 4800 K. The height at which the maximum temperature is observed on the LB is around 300 km. The height at which the maximum temperature along cuts 1 and 2 across the LB is about 5293 and 5075 K, while the same for cuts 3–6 is about 4800 K. The height at which the maximum temperature is observed on the LB is about 300–400 km (~log τ = −3) for cuts 1 and 2, while the same for cuts 3–6 is 600–700 km (~log τ = −4).

We find that the height variation of the temperature increases nearly monotonically along the length of the LB at t = 0 minutes. This changes at t = 7 and 11 minutes, where there is a bump close to the middle of the LB (Figure 11). At all three instances of time, the temperature enhancement at the southern end of the LB, with respect to the umbra, is at a lower height with values of about 1100 K at log τ ~ −3.5, while at the northern end, the values are about 640 K. The highest temperature near this southern section is at a height of about 500 km. The figure also indicates that the thermal enhancement at the southern end of the LB becomes elevated from t = 0 to t = 7 and 11 minutes at x = 2–6 Mm and extends over a height range of about 1 Mm. A cold upper region at the middle of the LB (x = 4–8 Mm) is located at about 600 km at t = 0 minutes (right column, bottom panel), which moves up to 800 km at t = 7 minutes and reaches 900 km at t = 11 minutes (right column, top).

Figure 12 shows 3D renderings of temperature from the SPINOR and IBIS data. The southern end of the LB is hotter than the northern end all the time. The S-shaped hook at the northern end is clearly seen as a continuation of higher temperature oriented at nearly 90° to the long axis of the LB (top left panel). The structure of the LB stays similar over the 11 minutes of DST observations with little differences between the IBIS and SPINOR results apart from the higher spatial resolution of IBIS.

4.3.3. Photospheric and Chromospheric LOS Velocities

Figure 13 shows persistent blueshifts of about 0.31 km s⁻¹ at the southern section of the LB as seen in the photospheric LOS velocity map derived from the SiI line (panel 3, column 1). This is consistent with what is observed in the HMI data (panel 4, column 1), although the latter are stronger and more conspicuous in the redshifted region of the limb-side penumbra. As seen earlier in Figure 2, there are weak redshifts at the northern end of the LB. These redshifts are more diffuse in the SiI line and are about 0.27 km s⁻¹. The umbra is relatively at rest in the photosphere as indicated in both panels. Panel 2 of column 1 shows the velocity derived from the line core of the SPINOR HeI line. There are strong redshifts of about 22 km s⁻¹ that extend from a patch to the west of its northern end. These redshifts are associated with the surges shown in Figure 2. Redshifts in the rest of the sunspot are about 2–6 km s⁻¹.

In general, the chromospheric redshifts follow the
This page discusses the properties of bright fibrils seen in the HeI line depth map (panel 1 column 1). The rest of the sunspot exhibits the regular and inverse Evershed flow in the photosphere and chromosphere, respectively.

The LB remains bright as seen in the CaII line core image over a duration of 11 minutes with several bright spikes directed to the west (panel 1, columns 2–4). Since the CaII spectra exhibit strong emission and redshifts, the velocity values are unreliable. Columns 5–7 of Figure 13 show the chromospheric LOS velocities derived from the IBIS Hα data. To put these velocities into context, Hα filtergrams in the line core as well as in the blue and red wings are shown in the figure (panels 2–4, columns 2–4). The bisector velocities derived from the IBIS Hα data reveal a rapid dynamic evolution of the surges in a span of 11 minutes. A large section of the surges shows redshifts of about 20–25 km s⁻¹ extending over an area of 31 Mm² at the 35% level at minute 0 (scan 02). The values are similar at the 52% and 68% levels as well. However, close to the line core, at the 94% level the redshifts reduce to about 10 km s⁻¹ and occupy a smaller area of about 4 Mm². The redshifts in this part of the LB also weaken significantly with time with blueshifts of 11 km s⁻¹ (at the 35% level), which reduce to about 6 km s⁻¹ as one approaches the line core. In contrast, the surges in the northern end of the LB along the bright fibril initially show blueshifts at lower line depths but change to redshifts of about 6 km s⁻¹ at t = 11 minutes.

4.3.4. LB Magnetic Properties

Figure 14 shows the magnetic field parameters derived from the FeI line of HMI as well as from the SiI and CaII lines from SPINOR. In the photosphere, the LB is associated with highly inclined magnetic fields that are about 500 G weaker than those of the adjacent umbra. However, it is found at the location of
the strong blueshifts at the southern end of the LB, where the azimuth and inclination maps from HMI render the LB significantly distinct from the rest of the sunspot. In addition, the polarization degree and linear polarization derived from the Si I line are highly reduced at that location. On the other hand, the above quantities are markedly enhanced when seen in the chromospheric CaII line.

Figure 15 shows the variation of the magnetic field over a cut across the blueshifted patch in the southern end of the LB. The reduction in magnetic flux seen in HMI is accompanied by an increase in linear polarization derived from the Si I line and highly reduced at that location. On the other hand, the above quantities are markedly enhanced when seen in the chromospheric CaII line.

Figure 15 suggests that the magnetic field in the LB drops off much faster with height than those in adjacent regions of the sunspot. The same is indicated by the value of the decay constant $\Delta B$ in Figure 14, which is smaller in the LB than in its surroundings. While the magnetic field is highly inclined in the LB as seen from HMI, it becomes relatively vertical with height, reducing from about $85^\circ$ to about $45^\circ$ in the Si I line that samples the upper photosphere. However, the field inclination in the LB is relatively higher than that in its adjacent neighborhood at the formation height of the photospheric Fe I and Si I lines as well as the chromospheric CaII line.

### 4.4. Long-term Temporal Evolution of the LB in SDO Data

As shown in Section 4.2.2, the LB forms rapidly between 15:48 and 16:48 UT on 2014 March 13. This is indicated in row A of Figure 16, which follows the temporal evolution of the LB between March 13 and 14. Panels 10 and 11 of row B indicate weak photospheric blueshifts of about 0.13–0.32 km s$^{-1}$ appearing at the broad base of the LB between 16:36 and 16:48 UT. These blueshifts stretch along the LB northward into the umbra but also extend nearly $5^\circ$ southward from the umbra–penumbra boundary into the penumbra in about 2 hr. The maximum value of the blueshifts at 18:48 UT is about 0.72 km s$^{-1}$ (panel 21), while the axial length of the LB where the blueshifts are observed is about $10^\circ$. At this point of time, the northern end of the LB is anchored to the adjoining penumbra. The broad base in the penumbra, from where the LB began to form, appears as a smooth extension of the LB. Panel 21 in the continuum intensity shows that even at HMI’s spatial resolution there are barb-like structures on the lower eastern edge of the LB ($x, y: 7^\circ, 18^\circ$).
While blueshifts dominate the LB, tiny patches of very weak redshifts, of about 0.16 km s\(^{-1}\), are observed at a couple of locations on the LB. One of these redshifted patches lies at the northern end of the LB close to the latter’s anchorage point at the umbra–penumbra boundary. This patch persists for at least 5 hr as seen in Figure 17. In the animation and panels 10–20 one can see it as a persistent small redshifted patch at the northern end of the LB that moves with its progression into the umbra. It could indicate the location of the other leg of the magnetic structure, similar to the pore with its redshifts. The other redshifted patches are comparatively more transient, lasting for about 30 minutes, and are seen at the edge of the LB near its midsection (panels 22–25 of Figure 16) and at the location of the barb described earlier.

Panels 26–39 show that the strongest blueshifts are confined to the southern section of the LB, while the northern end of the LB develops a strong curvature with a prominent S-shaped hook enclosing a larger umbra core than what was seen nearly 2.5 hr earlier. Although the southern section of the LB lacks the curvature exhibited by its northern counterpart, there is a very small, although discernible, increase in its curvature with time. The flanks of the blueshifted region in the southern part of the LB exhibit a pronounced intensity that is about 15% brighter than its penumbral surroundings. A similar feature is seen at the northern end of the LB, where the enhanced brightness coincides with the hooklike structure in the penumbra and lies adjacent to the blueshifted patch. The blueshifts reach a maximum value of about 0.85 km s\(^{-1}\), which occurs between 23:00 and 23:24 UT on 2014 March 13.

The onset of the blueshifts is also reflected in the magnetic field wherein the field strength in the LB is about 1500 G and 1200 G in the northern and southern sections of the LB, which is on average weaker than the adjacent umbral and penumbral magnetic fields by 1000 G and 300 G, respectively. The inclination is about 50°–60° in the upper and central parts of the LB. In the southern section of the LB the inclination is about 80°–85°, which is about 25° higher than that in the neighboring penumbra. However there are a few pixels in the southern part of the LB where the inclination is greater than 90°. In addition, the horizontal magnetic field is directed along the axis of the LB. Panels 32–39 of Figure 16 also show that as the curvature in the northern half of the LB becomes stronger, the values of the field strength become nearly indistinguishable from those in the adjacent umbra. The inclination maps also show a similar characteristic where the central and southern parts of the LB stand out more clearly than its surroundings.

Rows E–G of Figure 16 show the response of the upper photosphere, upper chromosphere, and transition region to the onset of the photospheric blueshifts in the LB. Panel 11 shows a remote brightening in the AIA 304 and 171 Å channels close to the eastern edge of the LB. This brightening occurs at 16:49 UT, about 13 minutes after the blueshifts appear in the photosphere. Panels 13 and 14 of row F show the bright patch intensifying and lying at the end of a dark filamentary structure, resembling a surge.

The AIA 1700 Å images in row E indicate the presence of discrete blobs of brightening on the LB (see panels 16, 26, and 28) that travel along the LB from its southern end to its northern end. In the animation of the temporal evolution
from the southern end of the LB, coinciding with the blueshifts, and terminates at the hooklike structure near the northern end of the LB, similar to the motion of the blobs seen in the 1700 Å channel. The typical length of the surges is about 5″, but they can at some instances be as large as 18″ (panel 21). More importantly the surges do not appear elsewhere in the sunspot, establishing a one-to-one correspondence and causal relationship between the photospheric blueshifts in the LB and the surges.

Figure 17 shows the LB in its decaying phase. The midsection of the LB begins to merge eastward with the neighboring penumbra, while the northern part of the LB starts drifting westward. The detachment of the northern section from the rest of the LB occurs at about 02:24 UT on 2014 March 14 (panel 59), while the southern section too has moved closer to the penumbra. While blueshifts are seen in the upper part of the LB, they are considerably weaker and the strongest blueshifts remain concentrated at the lower end of the LB. However, as the LB breaks up near its central part at 02:24 UT, the blueshifts in the southern part get considerably weaker with time. The brightness enhancement in the continuum intensity, along the hooklike structure, disappears with the breakup of the LB. However the enhanced continuum intensity persists in the southern part of the LB lying adjacent to the blueshifts and is observed until 06:12 UT on 2014 March 14. While the upper section of the LB is reduced to a chain of diffuse UD s, the southern part remains intact and attached to the penumbra. The last image available before the HMI data gap (panel 78) shows blueshifts of about 0.17 km s\(^{-1}\) at the southern section of the LB. The sunspot does not split as a result of the LB and remains as such until the early part of 2014 March 16.

The field strength maps in row C indicate that the signature of the northern part of the LB gets weaker and disappears at about 00:48 UT, which is 1.5 hr earlier than when the LB fragments at the center. However the values of the field strength in the lower section of the LB, where the weak blueshifts are seen, remain unchanged at 1200 G. Similarly, the value of the inclination at that location is about 80°. The surges are confined to the southern section of the LB as the latter detaches from the center during its decay phase.

The top panel of Figure 18 shows the evolution of magnetic flux in the leading sunspot as well as in the pore and the LB. The flux in the leading sunspot reduces by a factor of about 20% over a period of 65 hr from a value of 5.1 × 10\(^{21}\) Mx at 13:00 UT on 2014 March 12. As seen in Section 4.2.1, the flux in the pore increases rapidly over a duration of 12 hr from the beginning of March 13, reaching a maximum value of about −1.9 × 10\(^{20}\) Mx. The flux in the pore nearly remains constant until about 17:00 UT on March 13, after which there is a monotonic decrease in the flux. The onset of flux reduction in the pore coincides with the emergence of blueshifts in the LB, which is indicated by the dashed line in the figure.

The flux in the LB exhibits a sudden rise followed by a rapid decrease over a duration of 13 hr with a maximum flux of 3.6 × 10\(^{20}\) Mx at the start of March 14. The middle panel of Figure 18 shows the maximum blue- and redshifts in the LB and pore, respectively. The blueshifts in the LB evolve similarly to the magnetic flux, reaching the peak value nearly at the same time. The redshifts in the pore exhibit a similar trend with a maximum value of about 1.4 km s\(^{-1}\) that gradually decreases to 0.3 km s\(^{-1}\) toward the end of its lifetime.

Figure 15. Atmospheric properties along a cut across the LB. Top panel: Continuum intensity − 1 (black line) and LOS velocity (red line) from HMI. Second panel: LOS magnetic flux (black line) from HMI and linear polarization signal E of Si i at 1082.7 nm (red line) and of Ca ii IR (blue line). Third panel: Magnetic field strength B from HMI (black line), of Si i at 1082.7 nm (red line), and at three optical depths of log \( \tau \) = −1, −3, and −5 from Ca ii IR (blue to turquoise lines). Bottom panel: Magnetic field inclination \( \gamma \) from HMI (black line), Si i at 1082.7 nm (red line), and CA ii IR (blue line). The cut is oriented from east to west.
Using the blueshifts in the LB, the height to which its envelope rises at time $t_i$ is computed as $h(i) = h(i-1) + (t_i - t_{i-1}) \times V_{LB}$, where $i$ and $V_{LB}$ denote the time index and the blueshift in the LB, respectively. This is shown in the bottom panel of Figure 18 along with the distance of separation between the pore and the sunspot center (red crosses). The envelope reaches a height of $5\, Mm$ within $2.5\, hr$ of the first appearance of the LB and a total height of $29\, Mm$ over its lifetime of about $13\, hr$. This height is also equal to the distance of separation of the pore from the sunspot center, and we find that the blueshifts in the LB begin when the pore has attained this maximum separation. The inset in the bottom panel shows that the envelope has risen to a height of about $0.54\, Mm$ when surges first appear in the AIA images. At the time of the DST observations, nearly $3\, hr$ later, the envelope reaches a height of about $10\, Mm$.

5. Discussion

Sunspot LBs are regions where convective motions occur more vigorously than elsewhere in the sunspot. Depending on how deep the convective flows are present, the morphology of the LB can be either filamentary or granular as shown in the top panels of Figure 19, marked with a white rectangle. The formation of an LB can be attributed to the buildup of gas pressure through convection and is often preceded by the coalescence of UDs and intruding penumbral filaments that later develop into a larger coherent structure resembling an LB (Katsukawa et al. 2007). As convection becomes more vigorous, convective cells similar to those in the QS develop into a granular LB, wherein upflows occur over bright cells which are flanked by downflows (Rouppe van der Voort et al. 2010; Lagg et al. 2014). Filamentary LBs on the other hand exhibit either very weak flows or overall redshifts (dashed circles in panels 2–5 of Figure 19). A third category of structures that extend into the umbra is referred to as umbra filaments (UFs), which differ from granular or filamentary LBs with respect to morphology, temporal evolution, and magnetic field configuration (Kleint & Sainz Dalda 2013; Guglielmino et al. 2019).

While the evolution of filamentary and/or granular LBs is conceived to occur within a sunspot, i.e., in situ, another
possible way that LBs can form in sunspots is during the emergence of an AR. As shown by Toriumi et al. (2015b), weakly magnetized regions in the QS can get squeezed by adjacent emerging magnetic flux elements as they coalesce to form sunspots. In this scenario, the LB can exhibit a large-scale upflow that nearly extends along its entire span (panel 6 of Figure 19). These observations of Toriumi et al. (2015b) are consistent with results obtained from radiative magnetohydrodynamic simulations of flux emergence as described in Cheung et al. (2008, 2010).

In this article, the LB forms in a regular, well-developed sunspot with a simple magnetic configuration. The LB is a transient structure that survives for about 13 hr. The most outstanding feature of our observation is that the LB exhibits blueshifts along nearly its entire length with values of up to 0.85 km s\(^{-1}\) (panel 1 of Figure 19). The blueshifted structure extends across one part of the umbral core and into the limb-side penumbra, which is dominated by redshifts associated with the normal Evershed flow. We trace the formation of the LB to an emergence event nearly 17 hr earlier wherein one leg of the emergent structure is located near the outer penumbra of the sunspot and the other leg coincides with a pore in the QS just outside the visible sunspot boundary. As the pore recedes from the sunspot, a filamentary channel develops in the penumbra extending from the penumbra–QS boundary to the umbra–penumbra boundary, where the LB consequently forms.

The high inclination of the LB with its relatively lower field strength, compared to the umbra, renders it brighter than the rest of the sunspot as well as the QS from the upper photosphere to the lower chromosphere. The high-resolution chromospheric observations from the DST reveal that the thermal distribution across the LB is quite complex, with the boundary enclosing the hot structure changing dramatically along its length, across its width, and in time, over a duration as short as 11 minutes. We also find evidence from the thermal stratification that certain sections of the LB are disconnected from the photosphere, appearing nearly isolated at mid-chromospheric heights. These support the idea of a rising, hot structure wherein different sections are elevated at different heights. The observed inhomogeneous thermal structure of the LB could be attributed to the following. At the photosphere the LB comprises weak and highly inclined magnetic fields. However, the vertical extent of the magnetic field as well as that within the LB could be such that there may arise
small-scale electric currents that produce local enhancements in temperature. Additionally, the LB appears bright in the photospheric continuum, which would imply that the structure is hot, resulting from the emergence of subphotospheric flux. There could be an additional pressure gradient along the length of the LB if one traces the blueshifted patches or blobs that move from the southern to the northern end of the LB. A flow along such a structure elevated to different heights would disperse the thermal flux nonuniformly, which would render a complex 3D temperature distribution in the LB.

Figure 20 shows a sketch of the possible magnetic topology during the magnetic flux emergence and the LB existence. The distance of the pore from the sunspot increases from 17 to 30 Mm from \( t = -15 \) to \( 0 \) hr and remains at that value afterward. The integrated height corresponding to the maximal blueshift velocity in the LB increases from 0 Mm at \( t = 0 \) hr to 30 Mm at \( t = +15 \) hr. The MMFs between the pore and the sunspot partly have the same polarity as the sunspot. The pore shows persistent redshifts. The LB disappears about 13 hr after its emergence.

At the time of the DST observations, the envelope has risen to about 10 Mm. The thermal inversion traces increased temperatures at about 0.5 Mm at the southern end of the LB and at 0.8 Mm at the northern end. The magnetic field inclination at the southern end, where the \( G \)-band image shows penumbral grains at the outer penumbral boundary, could be oriented toward the umbra in the opposite direction of the surrounding magnetic field lines. Those field lines might be able to sustain an Evershed flow in the opposite direction toward the umbra. The blueshifts persist along the length of the LB up to the point where it turns 90° out of the plane of the figure in the S-shaped hook.

We now address the interaction of the emergent structure, corresponding to the LB, with the overlying umbral magnetic field. The appearance of photospheric blueshifts in the LB is accompanied by recurrent, and highly dynamic, surges in the chromosphere and transition region that start about 13 minutes later. Assuming an ascent speed of 1.0 km s\(^{-1}\) (the maximum blueshift is about 0.85 km s\(^{-1}\)), the loop would reach lower-chromospheric heights of 0.78 Mm in the above time span. Furthermore, the surges persist for the entire lifetime of the LB and cease completely when the LB dissolves. Thus our observations establish the causal nature of the surges with the photospheric blueshifts in the LB and explain the recurrent behavior of the surges as a direct consequence of a large-scale, nearly horizontal emergent structure within a sunspot. The physical attributes of the surges are in good agreement with Robustini et al. (2016), and the bodily motion can be due to the emergence of an LB that progresses from the south to the north. We find that the LB as a whole is hotter than the umbra along all of its length, while the surges are much more intermittent in both space and time. The increased chromospheric temperature of the LB is thus more likely to be due to the ohmic dissipation of electric currents (e.g., Tritschler et al. 2008) caused by the large magnetic field gradient to its surroundings rather than to the more transient surges. Earlier studies have suggested magnetic reconnection as the mechanism that drives the surges (Robustini et al. 2016; Tian et al. 2018), but determining the exact mechanism for the surges is beyond the scope of this article.

Apart from the surges, we do not observe any flaring activity associated with the onset of blueshifts in the LB during the emergence process, possibly due to the low flux content in the structure, accounting for just 4% of the sunspot. Transient jets, however, are seen during the early stages of the pore’s emergence as a result of small-scale magnetic reconnection with opposite-polarity patches being driven by the moat flow (Ma et al. 2015). The dissolution of the LB is possibly due to the counterclockwise rotation of the sunspot, wherein the northern and southern ends of the LB move in opposite directions and cause the LB to eventually break up near its midsection.

The physical characteristics of the LB described in this article suggest that it is closer to a UF rather than to a filamentary or granular LB. There are, however, distinct differences with the UF reported by Kleint & Sainz Dalda (2013) and Guglielmino et al. (2019). According to Kleint & Sainz Dalda (2013), UF are separate flux bundles that possibly connect the umbra to a network region outside the sunspot, wherein a siphon flow develops driving a counter–Evershed flow from outside the spot into the umbra. However, in their observations, the LB exhibits redshifts, with blueshifts confined...
Figure 19. Examples of LBs and their associated LOS velocities. Top panel: Hinode G-band images showing examples of penumbral (left) and granular (right) LBs. Bottom panels: HMI continuum intensity (left) and LOS velocity (right) of LBs in different ARs. The white dashed circles highlight the locations of the LBs. The FOV for all the bottom panels is the same, except for panels 1 and 3, which have an FOV of 120″ × 65″. The NOAA AR is indicated on the top left corner.
exclusive to the penumbral section of the sunspot, similar to the results of Guglielmino et al. (2019). In contrast, the LB described here has a persistent blueshift along all its length, which is compatible with an emergent structure, not a siphon flow. The outer footpoint of our emergent structure coincides with a pore that is redshifted, whereas a siphon flow ought to produce blueshifts at that location. Furthermore, Guglielmino et al. (2019) showed that the UF as well as the blueshifted penumbral region has an opposite polarity to the sunspot, whereas the magnetic field in the LB described here has the same polarity as the sunspot, albeit highly inclined. The southern section of the LB near the sunspot–QS boundary coincides with bright penumbral grains, which is not seen in Kleint & Sainz Dalda (2013). On the other hand, while this feature is present in Guglielmino et al. (2019), it is located further inward in the penumbra.

Kleint & Sainz Dalda (2013) also suggested that the brightness of UFs in the chromosphere is related to the dissipation that occurs in upper-photospheric or lower-chromospheric heights, which is compatible with the temperature enhancements we detect between 400 and 800 km. However, these enhancements do not originate from flares or other energetic phenomena as seen by Kleint & Sainz Dalda (2013).

Based on the above, one can distinguish LBs from UFs using the following criteria. UFs lack multiple convective cells and/or dark lanes or striations. In comparison to LBs, UFs are highly elongated, with a small radius of curvature, and are short-lived. In addition, if the UFs exhibit blueshifts along all their length, this must signify emergence. While our observations indicate that the structure in the sunspot umbra resembles a generic LB, it is part of a large-scale emergence event initiated just outside the sunspot. The magnetic association of an LB with an external structure is also observed in AR filaments that terminate close to the outer ends of sunspot LBs (Guo et al. 2010; Shimizu 2011; Ma et al. 2015).

Our results suggest that the sunspot magnetic field is more “gappy” at subphotospheric layers to facilitate flux emergence as shown by Louis et al. (2014b), where the rear half of a leading sunspot is connected to the following polarity of the AR, while the front half is rooted in the preceding AR. As a result of this unique magnetic connectivity, the leading sunspot eventually splits into two, nearly equal halves, with the front half separating and moving rapidly away from its twin. The delay in the formation of the LB nearly 17 hr after the pore’s emergence shows that magnetic pressure is quite strong, inhibiting the rise initially, but also fragmented at the subsurface, allowing the structure to eventually rise. The presence of a penumbral intrusion prior to LB formation possibly indicates a weakening of the umbral magnetic field, which is similar to that shown by Katsukawa et al. (2007). During its lifetime, we find the LB does not develop sufficiently to exhibit a granular morphology. Its physical properties and the large-scale external association with the pore render it atypical to what is generically referred to as LBs.

Our observation of an elongated LB in the umbra suggests that a sunspot should harbor subphotospheric structures that can emerge under suitable conditions on various spatial scales—in our case, on a scale comparable to the size of the sunspot. Such emerging magnetic flux can interact with the preexisting structure, leading to surges and possibly flares, presumably through magnetic reconnection. The flux emergence does not, however, destabilize the sunspot or disrupt its internal structure enough to trigger its decay. An extended study on additional cases of umbral flux emergence on different spatial scales might reveal any eventual impact on the lifetime of sunspots in contrast to sunspot decay due to erosion at the outer penumbral boundary (Simon & Leighton 1964; Litvinenko & Wheatland 2015).

6. Conclusions

The LB under investigation formed as a result of large-scale flux emergence wherein one leg of the emergent structure is rooted in a pore located in the QS, while the LB forms the flatter segment of the loop. The emergence is characterized by conspicuous blueshifts in the LB, whose southern end runs well into the limb-side penumbra, which is redshifted. The receding motion of the pore away from the sunspot is accompanied by the rise of an emergent LB in the solar atmosphere, which produces highly dynamic surges in the chromosphere and
Asai, A., Ishii, T. T., & Kurokawa, H. 2001, ApJL, 555, L65

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transition region. While the LB is hotter than the adjacent umbra by about 600–800 K, various segments of the LB are elevated at heights that vary between 400 and 700 km. The LB only survives for about 13 hr, while the highest field lines related to the flux emergence could reach a height of about 29 Mm in the solar atmosphere. Although the LB has a morphology similar to that of a penumbral intrusion in the umbra, its physical properties and its association with the pore make it an atypical LB. We suggest that the presence of large-scale persistent blueshifts in LBs can be used to distinguish those caused by large-scale structures that are driven by in situ magnetoconvection from those caused by large-scale flux emergence in a sunspot.

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ORCID iDs

Rohan E. Louis @ https://orcid.org/0000-0001-5963-8293
Christian Beck @ https://orcid.org/0000-0001-7706-4158
Debi P. Choudhary @ https://orcid.org/0000-0002-9308-3639

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