The Origin of Sequential Chromospheric Brightenings

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\begin{abstract}
Sequential chromospheric brightenings (SCBs) are often observed in the immediate vicinity of erupting flares and are associated with coronal mass ejections. Since their initial discovery in 2005, there have been several subsequent investigations of SCBs. These studies have used differing detection and analysis techniques, making it difficult to compare results between studies. This work employs the automated detection algorithm of Kirk et al. (Solar Phys. 283, 97, 2013) to extract the physical characteristics of SCBs in 11 flares of varying size and intensity. We demonstrate that the magnetic substructure within the SCB appears to have a significantly smaller area than the corresponding H\textalpha emission. We conclude that SCBs originate in the lower corona around 0.1\textit{R}\textsubscript{\odot} above the photosphere, propagate away from the flare center at speeds of 35 – 85 km s\textsuperscript{-1}, and have peak photosphere magnetic intensities of 148 ± 2.9 G. In light of these measurements, we infer SCBs to be distinctive chromospheric signatures of erupting coronal mass ejections.

\textbf{Keywords:} Flares, Dynamics; Chromosphere, Active
\end{abstract}

1. Introduction to SCBs

Two ribbon chromospheric flares observed in H\textalpha appear well-organized when first examined: ribbons impulsively brighten, separate, and exponentially decay back to pre-flare levels. Upon closer inspection of H\textalpha flares, there is often a significant number of compact brightenings in concert with the flare eruption that are spatially separated from the evolving flare ribbon. One class of these off-ribbon chromospheric brightening was first classified by Balasubramaniam et al. (2005) in a 19 December 2002 M2.7 flare. Using a multi-wavelength data set to analyze the 19 December flare and eruption of a large scale trans-equatorial loop, Balasubramaniam et al. (2005) observed a large scale coronal dimming,
flares in both the north and south hemispheres, and a halo coronal mass ejection (CME). In Hα images of the same event, the loop eruption manifested itself as flare precursor-brightenings, sympathetic flares, and cospatial propagating chromospheric brightenings. Termed sequential chromospheric brightenings (SCBs), the speed of this propagating disturbance was measured to be between 600 – 800 km s\(^{-1}\). Although the disturbance propagated at similar speeds to extreme ultraviolet (EUV) flare waves, they differed from typical waves observed in Hα (Moreton waves) in that they were not observed in off-band images, had an angular propagation width of less than 30°, and appeared as distinctly individual points of brightening instead of continuous fronts (Kirk et al., 2012a).

Kirk et al. (2013) refined the technique and developed a systematic method for identifying and measuring properties of SCBs by employing an automated detection and tracking algorithm. They concluded that SCBs originate during the impulsive rise phase of the flare and often precede the Hα flare intensity peak.

Kirk et al. (2013) discovered that the nature of SCBs are phenomenologically distinct from other compact brightenings observed in the chromosphere due to their impulsive intensity signatures, unique Doppler velocity profiles, and origin in the impulsive phase of flare Hα intensity evolution. Kirk (2013) and Kirk et al. (2014) found that SCBs are a type of localized chromospheric heating and ablation due to impacting coronal plasma and have associated temperatures of \( T \approx 10^5 \) K. As an ensemble, SCBs are tracked to propagate outward, away from the flare center, at velocities between 41 – 89 km s\(^{-1}\) (Kirk et al., 2012b).

Between the initial parametrization of SCBs in 2005 and 2007, and contemporary work completed in the past few years, several inconsistencies have emerged in the stated characteristics of SCBs. Specifically, Balasubramaniam et al. (2005) found SCB propagation speeds to be between 600–800 km s\(^{-1}\) while Kirk et al. (2012b) found more modest speeds of 41 – 89 km s\(^{-1}\). Also, Balasubramaniam et al. (2006) found SCBs to be related to their host flare only in 65% of the cases studied and postulated that “...SCBs are not a direct consequence of flares,” which differs from the empirical models of Kirk et al. (2012b) and Pevtsov, Balasubramaniam, and Hock (2007). Furthermore, both Balasubramaniam et al. (2006) and Pevtsov, Balasubramaniam, and Hock (2007) find SCBs to have a stable mono-polarity in the corresponding photospheric magnetic field yet do not present any data in the associated magnetic field strength. Without an a priori bias, this research looks to find statistically significant magnetic substruc-
Section 2 describes the events and data incorporated into this study. Section 3 briefly explains our methods of feature detection and data assimilation. Section 4 presents the physical characteristics of flares and associated SCBs along with potential field source surface modeling of SCBs. Sections 5 and 6 discuss the physical results of the data and the conclusions we draw from them.

2. Events Examined

We selected 11 chromospheric ribbon flares to analyze the characteristics of SCBs, which are listed in Table 1. These events had a favorable viewing geometry with the entire flaring region visible on the solar disk as well as full temporal coverage from the ground-based Hα telescope. Section 2.1 further discusses the details of Hα observations. The photospheric magnetic field of each event was gleaned from cotemporal magnetograms. Section 2.2 addresses the specifics of the treatment of the magnetic field data. The Geostationary Operational Environmental Satellite (GOES) measured flare class of each event varied greatly, ranging from no detectable soft X-ray signature in two events, to as large as an X10.0 flare. Corresponding coronagraph images were analyzed for each event to visually search for a CME associated with the flare eruption. Data about the associated CMEs was ascertained from an automated characterization software package and is further discussed in Section 2.3. Both the GOES class and the existence of a visual CME also are listed in Table 1. In this work, we are using the term “flare eruption” to include both the overall evolution of the Hα flare ribbons as well as the impulsive appearance SCBs located outside of the flare ribbons.

Of the 11 flares selected for this study, all but two had been previously examined by Balasubramaniam et al. (2005), Balasubramaniam et al. (2006), Kirk et al. (2012a), Kirk et al. (2012b), or Kirk et al. (2014). This reanalysis of events will provide two benefits. First, all events are analyzed with the same automated suite of software. This makes the results from each event directly comparable to each other without needing to account for biases within the software or analyst. Second, a comprehensive investigation of photospheric magnetic fields has not been completed for any of the events being studied. This investigation will compile magnetic field data of SCBs, filling a gap in our knowledge of these phenomena.

2.1. ISOON Hα

This study examines chromospheric flares and their associated SCBs with Hα (6562.8 Å) images recorded by the Improved Solar Observing Optical Network (ISOON; Neidig et al. 1998) prototype telescope. ISOON is a ground-based, semi-automated instrument, imaging the full-disk with 1.1 arcsec pixel resolution at a one-minute cadence. Each 2048 × 2048 pixel image is normalized to the quiet Sun and corrected for atmospheric refraction. Immediately subsequent to recording the Hα line center images, ISOON also takes two off band images in the red and blue wings of the line at ±0.4 Å. These wing images are then translated
Table 1. The events used in this work to investigate the automated identification and tracking of SCBs and flare ribbons. The time listed is the start time of the flare or filament eruption in Hα. The heliographic Stonyhurst (HGS) coordinates of the approximate centroid of each event is listed for reference. Nine of the eleven events were previously identified by Balasubramaniam et al. (2005), Balasubramaniam et al. (2006), Kirk et al. (2012a), Kirk et al. (2012b), or Kirk et al. (2013) labeled Ba, Bb, Ka, Kb or Kc respectively, while two are new in this study. The data sources utilized for each event are abbreviated as: I (for ISOON), L (for Large Angle and Spectrographic Coronagraph (LASCO)), G (for GOES), M (for Michelson Doppler Imager (MDI)), H (for Helioseismic and Magnetic Imager (HMI)), and C (for Computer Aided CME Tracking (CACTus)).

| Event Date | Time UT | HGS Coordinates | GOES Class | Visual CME | Data Sources | Previously Studied |
|------------|---------|-----------------|------------|------------|--------------|-------------------|
| 19 Dec. 2002 | 21:34 | 9°W, 15°N | M2.7 | yes | I, L, G, M, C | Ba and Kb |
| 6 Mar. 2003 | 15:08 | 0°W, 27°N | None | no | I, L, G, M | no |
| 9 Mar. 2003 | 15:18 | 1°E, 35°N | B6.6 | yes | I, L, G, M, C | Bb |
| 11 Jun. 2003 | 17:27 | 23°E, 16°S | M1.8 | no | I, L, G, M | Bb |
| 29 Oct. 2003 | 20:37 | 9°W, 19°S | X10.0 | yes | I, L, G, M, C | Bb |
| 9 Nov. 2004 | 16:59 | 51°W, 8°N | M8.9 | yes | I, L, G, M, C | Bb and Ka |
| 6 May 2005 | 16:03 | 28°E, 9°S | C8.5 | yes | I, L, G, M, C | Bb and Ka |
| 13 May 2005 | 16:13 | 11°E, 12°N | M8.0 | yes | I, L, G, M, C | Ka |
| 6 Dec. 2006 | 18:29 | 63°E, 6°S | X6.5 | yes | I, L, G, M, C | Kb |
| 6 Nov. 2010 | 15:30 | 58°E, 19°S | M5.4 | yes | I, L, G, M, H, C | Kc |
| 30 Nov. 2010 | 17:35 | 39°E, 15°N | None | yes | I, L, G, M, H, C | no |

To fully capture the rise and decay of the flare, images were extracted from the archive beginning approximately an hour before the beginning of the flare eruption and extending an hour after the flare decayed back to pre-flare intensity levels in Hα. This yielded a data cube with between 400 and 1600 images for each event.

2.2. Magnetograms

Photospheric magnetic field measurements are made with the Michelson Doppler Imager (MDI: Scherrer et al. 1995) which is a space-based polarimeter on the Solar and Heliospheric Observatory (SOHO) satellite. MDI images the NiI line at 6768 Å every 96 minutes on a 1024 × 1024 pixel CCD with a spatial mapping of 2 arcsec per pixel using a pair of tunable Michelson interferometers.

For the two events in 2010, high-resolution photospheric magnetic field measurements are available using the Helioseismic and Magnetic Imager (HMI: Scherrer et al. 2011). HMI has significantly higher spatial and temporal resolution than MDI. HMI uses a photospheric FeI line at 6173.3 Å and images the Sun on a 4096 × 4096 pixel CCD with a spatial scale of 0.6 arcsec per pixel. Images are recorded at a cadence of 45 seconds and have a 10 G precision.
We process the raw data into their vector components using the HMI Vector Magnetic Field Pipeline (described by Hoeksema et al., 2014) and end up with six images temporally spanning each event. We select the image nearest to the timing of the peak Hα emission of each SCB for this analysis.

2.3. CME Data

Coronagraphic images from the SOHO Large Angle and Spectrographic Coronagraph (LASCO Brueckner et al., 1995) C2 instrument are used to visually identify CMEs emerging from the identified Hα events. LASCO is a white light coronagraph, which images the corona from about 1.5 to 6 solar radii. The Computer Aided CME Tracking (CACTus) package is an autonomous software package that detects and characterizes emerging CMEs in LASCO (Robbrecht, Berghmans, and Van der Linden, 2009). CACTus detects erupting CMEs and records the central position angle, angular width, and makes a velocity estimation for each CME.

3. Analysis Techniques

Each of the flares considered in this study demonstrate several similar physical characteristics. Bright flare ribbons materialize from the active region, separate from each other, undergo an exponential decay in their luminosity, and evolve their topology. Concurrent to the onset of the Hα flare, several types of compact brightenings are observed in the flaring region. Through careful filtering, we select only those brightenings that exhibit the characteristics of SCBs described in Balasubramaniam et al. (2005), Balasubramaniam et al. (2006), and Kirk et al. (2012a). Next, we employ a Lagrangian approach to identify and trace resolvable subsections of the flare ribbons and SCBs as they appear, disappear, and evolve throughout the eruption. This process was initially developed and documented by Kirk et al. (2013). These identification processes are designed to analyze specifically the Hα images from ISOON and are described in Section 3.1.

By definition, SCBs are sequential in nature (Balasubramaniam et al., 2005). Thus, one SCB does not itself characterize the evolving flare environment. Section 3.2 describes the semi-autonomous forward-fitting algorithm developed to distinguish populations of SCBs and determine their collective propagation velocities.

Subsequent to the identification of SCBs in Hα, the spatial locations of these points are overlaid on complementary magnetograms from MDI. A potential-field-source-surface (PFSS) model (Schrijver and De Rosa, 2003) is then applied to extrapolate the chromospheric and coronal magnetic field lines originating from these locations. A description of the PFSS model used is in Section 3.3.

3.1. Tracking Algorithm

There are two steps needed to extract individual kernels from Hα images: detection and tracking. A kernel is defined in this work to be a small locus of pixels...
that have increased intensity, which can be isolated from other pixels in the immediate vicinity. The detection algorithm identifies preliminary bright kernels in a set of images by eliminating pixels that are dimmer than a specific intensity (1.35 times background intensities for flares and 1.2 for SCBs) as empirically determined by Kirk et al. (2013). Both low and high spatial bandpass filters are applied to isolate features and suppress noise. Each preliminary kernel does not have any predetermined size or shape, but does have a local maximum and is isolated from its nearest neighbors by at least one “dark” pixel. Next, properties of the candidate kernels are calculated: integrated intensity, radius and eccentricity. The candidates are then filtered by size, shape, and intensity to eliminate unwanted features such as broad regions brightening in concert or single pixel detections of noise. For a complete discussion of the process of kernel detection and filtering, see Kirk et al. (2013).

The second step in flare and SCB kernel extraction process is linking time-resolved kernels between individual frames in Hα. These trajectories allow us to isolate single kernels and follow their evolution through time. We employ a diffusion-based algorithm to statistically associate similar kernels between images. This tracking technique was initially developed by Crocker (1996) and subsequently modified by Kirk et al. (2013) for tracking solar features. This statistical approach maximizes the probability that a single particle with classical Brownian motion will diffuse within a set range of distances in a given segment of time. The diffusion probability is generalized for a system of any number of non-interacting particles. This probabilistic approach to tracking yields trajectories for all identified kernels at once. Once initial trajectories are identified, a filter is applied to eliminate weak detections lasting less than a minimum number frames (see Kirk et al. 2013 for a complete description). This temporal filter eliminates off-ribbon flare detections which are associated with the eruption but do not characterize the evolution of the flare ribbons and SCB kernels that have ambiguous definition (i.e. they could be flare kernels).

The end result is a set of flare and SCB kernels that individually appear stochastic, yet fully represent and characterize the evolving flare region as an ensemble and allow us to extract quantities of interest such as location, velocity, and intensity of subsections of the flare ribbons and individual SCBs.

3.2. Forward Fitting

To identify groups of SCBs and characterize their propagation, a slope is required to be fit to the time-distance SCB data set. A simple regression analysis is impossible in this situation because multiple populations of SCBs may exist in the same data set. A more complicated mixture modeling technique is also unreliable because there is a relative small number of SCBs detected which leads to large statistical uncertainties and ambiguous group identification. Therefore, we employ a supervised, iterative, forward-fitting technique, similar to a linear

\[ \text{radius} = \text{radius of gyration} \]

The calculation of a kernel “radius” is more accurately a “radius of gyration” and is calculated by finding the mean intensity weighted radius from each pixel to the kernel axis of rotation. See Crocker (1996) for further details.
discriminate analysis. This method requires the user to first, visually determine
the number of groups to be fitted, and second, identify the approximate location
of each group. The forward-fitting routine then searches all linear combinations
of features for the next “best point” to include in each of the groups, which
minimizes the $\chi^2$-value to the identified group. This process is then repeated
with each of the groups that now include points from the previous iteration.
Repeating this method over all the points in the set produces an ordered set of
points that when sequentially fit, have an increasing $\chi^2$-value.

This iteration allows us to view the set of SCB data in $\chi^2$-space by char-
terizing how a selected group variance changes as each point in the set is
added. Selecting the groups in the $\chi^2$-curve has the effect of identifying where
the variance within a group begins to increase dramatically. The derivative of
the $\chi^2$ distribution is then taken and the point in which this curve increases to
beyond one standard deviation is selected to divide the population of one group
from the rest of the set. Running this routine several times, each time selecting
the same groups, minimizes the effect of the user and provides an estimate of
the error associated with the group identification.

This method has two caveats. First, this fitting method relies on the detec-
tions having Poissonian noise. This presumption is imprecise, since the detection
process of compact brightenings introduces a selection bias. Second, the fitting
method assumes that no acceleration occurs in the propagation of SCBs. This is a
reasonable first-order approximation from the studies of SCB group propagation
by Balasubramaniam et al. (2005).

3.3. Potential Field Model

Polarimeters are used to infer the photospheric magnetic fields because that is
the only place in the solar atmosphere with consistently adequate light intensity
to measure polarization. To extrapolate the inferred photospheric magnetic field
to the rest of the upper atmosphere, a model is needed. The simplest model is
the potential-field-source-surface (PFSS) which assumes a potential atmosphere
that is current-free. The challenge for any model is to find the current free scalar
potential in a spherical geometry.

Schrijver and De Rosa (2003) developed an assimilation PFSS model to ex-
trapolate a current-free potential within a spherical volume between $r = 1 R_\odot$
and $r = 2.5 R_\odot$ given an initial photospheric magnetic field\footnote{DeRosa’s PFSS modeling software package is currently available at www.lmsal.com/~derosa/pfsspack/}. The model derives
a unique solution for a given domain and boundary conditions both at the top
($r = 2.5 R_\odot$) and bottom ($r = 1 R_\odot$). At the upper boundary condition the
field is assumed to be purely radial. The lower boundary condition field is de-
rived from an evolving surface-flux transport model \cite{Schrijver2001}. Synoptic
magnetograms from MDI are used to anchor the model in the photosphere. The
flux transport model then assimilates the photospheric field through the entire
domain by advecting the flux stepwise vertically across the full solar surface.
It empirically determines differential rotation, meridional flow, and convective
Table 2. General physical characteristics of individual flare and SCB kernels. “Ensemble Motion” refers to the motion of an individual kernel as compared to its nearest neighbors over the kernel lifetime.

| Kernel Type | Minimum Diameter | Peak Intensity Increase | Average Lifetime | Ensemble Motion |
|-------------|------------------|-------------------------|------------------|-----------------|
| Flare       | 6.4 Mm           | ≥ 1000%                 | ≈ 120 min        | Directional Consistency |
| SCB         | 1.6 Mm           | ≤ 250%                  | ≈ 10 min         | Random Walk     |

dispersal profiles from the input data, using a non-linear algorithm to account for fragmentation and collision of flux. The result of the PFSS model is a 3D projection of the magnetic field in which field lines can be drawn. This model is limited to locations where the field is potential, which is most accurate in the quiet Sun and least accurate in flaring regions where a significant current sheet is generated.

4. Physical Results of Algorithm Application

Applying the detection and tracking algorithm to the 11 flaring events, we identified a total of over 10,000 discernible flare kernels and over 4,000 discrete SCBs in Hα images. Sequential chromospheric brightenings, although related to the erupting flare ribbons, are distinctly different from the flare kernels. The differences between these two types of brightening in the chromosphere is outlined in Table 2. Individual SCBs are much more fleeting, smaller, and dimmer than the flare ribbons. A typical SCB lasts less than 10 frames (corresponding to 10 minutes) above the detection thresholds in ISOON Hα, while flare kernels last on average over 120 minutes. The diameter of the smallest resolvable kernel along the flare ribbon is approximately 6400 km as compared to SCBs that are resolved down to a 1600 km diameter. A typical SCB has a peak intensity of 1.2 – 2.5 times brighter than the average background intensity level. In contrast, flare ribbons often brighten more than an order of magnitude above the pre-flare brightness.

When the individual tracks of SCB kernels are examined, they do not show any progressive motion. The centroid of an SCB kernel randomly “walks” around within about six pixels of its starting location for the duration of the trajectory. Although the ensemble of SCBs demonstrate a sequence of point brightenings, giving the appearance of a progressive traveling disturbance, the bright emission of an individually measured SCB does not follow the disturbance and remains in the same location. Similar to a wave, the medium in which SCBs are measured remains laterally undisplaced with the apparent propagation of the brightenings. This result confirms the findings of Balasubramaniam et al. (2005) and Kirk et al. (2012b).

In addition to these initial results of detection, further insight into the physical processes of the eruption can be gleaned with closer analysis. These are
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Figure 1. Time evolution of the 19 December 2002 event. The dashed line marks the peak Hα flare intensity. The blue line is the Hα flare kernel intensities integrated at each time step. The redish line plots the SCB kernel intensities (multiplied by a factor of 10 for display purposes) integrated at each time step. Plotted for reference in black is the GOES 1.0 – 8.0 Å intensity curve.

presented in the following two sections: those determined from Hα (Section 4.1) and the results of overlaying the detections on corresponding magnetograms (Section 4.2).

4.1. Findings in Hα

It is simple to recover the total Hα flare intensity curve since the flare kernels are just fragments of the entire flare. Summing each flare kernel results in an intensity evolution in Hα that is comparable as to the X-ray intensity, the impulsive rise, and decay phase of the flare measured with GOES. Summing each SCB kernel results in an intensity curve that has characteristics comparable to the Hα flare intensity and X-ray intensity curves, yet is distinct. Figure 1 plots this aggregated intensity of the entire population of flare kernels and SCB kernels versus time as well as the GOES X-ray intensity in the 19 December 2002 event. In this case, the SCB aggregate intensities peak well before the flare does. The peak of the aggregate SCB intensity curve occurred before or concurrent with the peak Hα flare intensity in 73% (representing 8 in 11) of the cases studied (Table 3).

This analysis of Hα flares yields a couple of interesting results on this well-studied topic. These are discussed in Section 4.1.1. Separating SCBs from their corresponding flares also allows comparison and contrast between SCBs of differing events and is discussed in Section 4.1.2.
Figure 2. A histogram of the continuance of detected flare kernels in all 11 events. Flare kernels are tracked for a mean duration of 122 minutes (long and short-dashed line) and a median duration of 111 minutes (dashed line).

4.1.1. Properties of Hα Flares

A result of parsing flare ribbons into kernels is that the temporal integrity of flare substructure is exposed. Distinct Hα flare kernels are temporally robust, lasting on average $\approx 122$ minutes each and had a most probable duration of 46 minutes (Figure 2). This average duration of a single kernel is shorter than the lifetime of the total Hα flare (from the impulsive phase, through peak intensity, and return to pre-flare brightness). Thus, the number of detectable kernels declines as the flare’s intensity decays from its peak, implying that there are fewer resolvable components in the flare ribbons as the flare evolves. This change in detectable kernels implies that the majority of kernels cannot be tracked from pre-flare to post-flare, suggesting a dynamic substructure to the flare ribbons when bright points appear and disappear as the flare erupts. 

Kirk et al. (2012b) also found that individual subsections of flare ribbons can be tracked and are observed to appear and disappear as the underlying flare ribbons evolve. Examining individual kernel structure suggests there is substructure within a flare ribbon whose elements impulsively brighten and dim within the integrated Hα flare intensity curve. These results support the premise that flare ribbons are composed of several magnetic field lines successively reconnecting and depositing energy in the chromosphere (e.g. Priest and Forbes, 2002). There is no evidence to claim an individual flare kernel is directly tracking one of these reconnections or a single post-flare loop footpoint. Thus, within a tracked flare kernel, multiple coronal reconnection events may be superimposed to produce the observed duration of a single flare kernel. Contemporary studies of flare ribbon substructure in the transition region have resolved unique features with a spatial scale of $\approx 2$ Mm and duration of 2–3 minutes (Brannon, Longcope, and Qiu 2015).
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4.1.2. Properties of SCBs

The number of SCBs identified in a given event varied greatly from as few as 48 to as many as 1335 (Table 3). Individual SCBs have light curves that are typically impulsive with a sharp peak – followed by a return to background intensity with a median duration of 6.6 minutes and a most likely duration of 2.1 minutes (Figure 3).

SCBs are more closely related to the impulsive phase of the H\(\alpha\) flare than any other part. However, many SCBs precede even the earliest onset of the associated flare. Figure 4 shows a typical example where SCBs brighten in a relatively short period of time before quickly decaying to an enhanced but consistent intensity. In 10 out of 11 flares examined, SCBs begin brightening in the impulsive phase of the H\(\alpha\) flare, with a peak occurring between 30 minutes and concurrent with the H\(\alpha\) flare peak intensity, returning to an idle intensity in the early decay phase, about 30 minutes after the peak (Table 3). In contrast, the H\(\alpha\) flare intensity curve remains above quiescent levels for several hours.

SCBs tend to cluster together in time-distance plots in all events. In Figure 3, the shade of the mark (from violet to green) corresponds to the intensity of the SCB measured. The closer the color of the mark is to green, the brighter the SCB. Generally, the brighter SCBs are spatially closer to the flare center and temporally closer to the H\(\alpha\) flare peak intensity. This intensity correlation is weak and is more closely related to distance rather than time of brightening.

Applying the forward-fitting technique to these data sets yields three propagation speeds: slow propagation, fast propagation, and surge propagation. The dashed lines in Figures 3 visually show the groups identified and Table 3 lists the results. Slow propagation of less than or equal to 100 km s\(^{-1}\) was measured in 64% (7 of 11) of the events. Their velocities ranged from 36.3 to 84.8 km s\(^{-1}\) (a tenuous measurement of velocity, 95.7 ± 40 km s\(^{-1}\), occurred in the 11 June 2003 event but we exclude it in this discussion because of the large errors associated). A fast propagation was measured in 64% (7 of 11) of the events. More than half
Table 3. Derived physical measurements for SCBs in each event. Propagation velocities without stated uncertainties were marginal with a high amount of marginal SCB detections.

| Event Date | Number of SCBs | SCB Velocity vs. Eruption | SCB Timing | Mean ΔMDI | CME Speed |
|------------|----------------|--------------------------|------------|-----------|-----------|
| 19 Dec. 2002 | 562 | 84.8 ± 9.7 | Before | 1.8 | 697 |
| 6 Mar. 2003 | 684 | 220 ± 143 | Coincident | -2.5 | - |
| 9 Mar. 2003 | 57 | 73.9 ± 10.9 | After | -0.5 | 187 |
| 11 Jun. 2003 | 281 | 95.7 ± 40.0 | After | 1.7 | - |
| 29 Oct. 2003 | 1335 | 460 | Coincident | -6.7 | 2029 |
| 9 Nov. 2004 | 302 | 36.3 ± 7.2 | Before | 5.9 | 1562 |
| 6 May 2005 | 171 | 63.0 ± 15.8 | Before | -4.7 | 917 |
| 13 May 2005 | 154 | 153 ± 55.8 | Coincident | 12.2 | 553 |
| 6 Dec. 2006 | 291 | 851 | Before | 0.5 | 984 |
| 6 Nov. 2010 | 210 | 65.4 ± 4.8 | After | -6.2 | 206 |
| 30 Nov. 2010 | 48 | 51.0 ± 4.9 | Before | 3.6 | 282 |

(6 of 11) of the events exhibited two types of propagation simultaneously. Just two events demonstrated fast propagation without a slow group as well. These fast speeds ranged from 153 to 851 km s\(^{-1}\) and typically had large relative errors associated with them. Two events (11 June 2003 and 29 October 2003) had a surging propagation groups identified. Both of these measurements were on the order of the coronal Alfven speed, at over 1000 km s\(^{-1}\), and had errors larger than the measurement. The 9 May 2003 event was the only event measured to have a negative slow propagation velocity, meaning that SCBs were approaching the flare.

4.2. SCBs in Magnetograms

Previous studies including Balasubramaniam et al. (2006), Pevtsov, Balasubramaniam, and Hock (2007), and Kirk et al. (2012b) all suggest that SCBs are strongly monopolar based on an empirical model. To extend these findings, photospheric line-of-sight (LOS) magnetic field measurements from MDI and HMI were extracted from the same region of interest identified in ISOON (Figure 6). The locations and spatial footprint of the identified SCBs were overlaid onto the magnetograms and mean magnetic fields calculated for each SCB. The results of magnetic field measurements using MDI are presented in Section 4.2.1 which provide the basis for modeling of the magnetic field out of the photosphere (presented in Section 4.2.3). The measurements of the vector magnetic field for the two events in 2010 are presented in Section 4.2.2.
Figure 4. The distance at which the bright point occurs versus time from the Hα flare peak for SCBs during the 19 December 2002 event. The color of each plotted point is representative of its relative intensity: the dimmest are purple, higher intensity detections are blue, and the highest intensity detections are green. The black dashed lines show two weighted regression fits: $84.8 \pm 9.7$ km s$^{-1}$, $260 \pm 19.4$ km s$^{-1}$.

4.2.1. MDI Measurements

The majority of the photospheric SCB magnetic field have a range between $\pm 50$ G. A histogram of individual SCBs measured magnetic intensity is plotted for the 6 November event in Figure 5. The mean of the magnetic field measurements for all events are also reported in Table 3, ranging from $-6.7$ G in the 29 October 2003 event to $12.7$ G in the 13 May 2005 event. Magnetic intensity histograms of each event show some substructure, suggesting multiple groups of SCBs within a single flare. If SCBs did exhibit strong monopolarity, a histogram of magnetic field measurements should have a bifurcated distribution. The population of measurements observed did show a weak bias toward one polarity; however, the most common measurement was always $\pm 0.5$ G around 0 G in every event except 6 May 2005. There is also no apparent correlation between SCB Hα and magnetic intensities. These findings contradict the empirical model of previous studies in that brightness and location of SCBs are not directly related to magnetic polarity or intensity. These older measurements do show that a typical individual SCB has a distinct non-zero magnetic polarity.

4.2.2. HMI Measurements

There were two events in 2010 where the SCB detections had cotemporal HMI magnetograms. We further processed these magnetograms into their vector components: $\vec{B}_\phi$ zonal, $\vec{B}_\theta$ meridional, and $\vec{B}_r$ radial (see Section 2.2). The events
on 6 November and 30 November had 210 and 48 individual SCBs detected respectively, which represents about 6% of the total number of SCBs detected in all events. Thus these measurements of SCB vector magnetic components in 2010 may not be representative of all SCBs, but do give us some significant insight beyond magnetic field measurements in MDI.

The power of measuring magnetic fields using the higher resolution of HMI is demonstrated in Figure 6. The pixel scale of MDI is too coarse to include more than a few pixels to measure the magnetic intensity. HMI has superior resolution both in the spatial direction but also in measuring the magnetic flux. MDI is insensitive to the small-scale variations of magnetic flux within the boundary of the SCB. Figure 6 graphically shows that there is substructure within an SCB that has gone previously unobserved using MDI. To demonstrate that the distribution of these magnetic elements is not purely statistical noise, we calculate the skewness and kurtosis within each SCB (see discussion in the following paragraphs). The mean magnetic flux of the SCB measured in each of these magnetograms is comparable, but the extrema are significantly different. Using HMI, a small negative magnetic feature is clearly visible completely bounded by the SCB. This feature is not apparent in MDI.

The population of HMI LOS pixels over all SCBs is regularly distributed. The skewness averaged over each HMI measurement is near zero ($\langle \gamma_1 \rangle = 0.03$) indicating that the HMI measurements en masse are uniformly distributed about their mean value. In other words, in a conglomerate of all SCBs, the positive and negative polarities are equally represented. This does not mean that within a given SCB, the skewness is near zero. The standard deviation of the skewness measurements over all SCBs ($\sigma_{\gamma_1} = 0.35$) indicates there are significant numbers of individual SCBs with positive or negative skewness. The near-zero average

![Figure 5](image_url). The distribution of photospheric LOS magnetic field intensities in MDI beneath SCBs for the 6 November 2010 event with a mean magnetic intensity of -6.2 G and a median of -5.1 G.
The Origin of SCBs

skewness combined with the average distribution of HMI pixels measured near
zero (Figure 7) means that SCBs *en masse* do not have a preferred polarity.

To calculate how likely an extreme value is to occur, we calculate the kurto-
sis. The excess kurtosis aggregated over each SCB measurement is consistently
platykurtic ($\langle \text{Kurt} \rangle = -0.63 \pm 0.23$). This means that outliers in the tails of this
distribution are less likely to occur because of random statistical noise. Given the
typical values of the mean, skewness, and kurtosis, a magnetic extrema
measured within the SCB boundary has a greater significance than its naively
calculated standard error. The magnetic extrema within an SCB have values
that are typically five standard errors beyond the mean value of the population
($B_{\text{max}} = \langle \vec{B}_{\text{SCB}} \rangle + 5.2\langle \text{S.E} \rangle$). The calculation of the standard error assumes a
Gaussian model, which overestimates the likelihood in the tails of our platykurtic
distribution, so the true standard error is likely to be smaller and the extrema
significance greater (> 5.2). The extrema selected have significantly stronger
magnetic flux as compared to the rest of the HMI pixels within the bounds of
an SCB.

Magnetic extreme values measured within an SCB have statistical signifi-
cance, which makes them a logical choice to isolate from the other pixel values
measured. Given the statistical significance (a typical value > 5.2 standard
errors above the mean) of the extreme values within each SCB, it naturally
follows to infer a physical meaning to the reason why an SCB contains such
magnetic outliers. These outliers imply that magnetic footpoints of an SCB in
the photosphere is significantly smaller than the corresponding area of the Hα
chromospheric brightening.

Figure 7 shows the distributions of the zonal, meridional, and radial magnetic
field components under SCBs in the 6 November 2010 event. We report the
magnetic field components in two ways. First we calculate the mean magnetic
field component magnitude over a given SCB area: ($\vec{B}_{\theta,\text{SCB}}$), ($\vec{B}_{\phi,\text{SCB}}$), and
($\vec{B}_{r,\text{SCB}}$) (Figure 7 top). Then we identify the pixel with the largest magnetic field

![Figure 6. An example of a single SCB from the 6 November 2010 event isolated in MDI and HMI. The boundary of the SCB is determined by the flux in Hα and then overlaid on the respective photospheric magnetogram to isolate the magnetic signature of the SCB. Both images are plotted on the same intensity gray scale shown on the right.](image)
Figure 7. The distribution of photospheric vector magnetic field intensities beneath SCBs for the 6 November 2010 event. The dashed lines show the mean intensity of each distribution. The top row averages the HMI vector components within each SCB: $\langle \vec{B}_{\phi,SCB} \rangle$, $\langle \vec{B}_{\theta,SCB} \rangle$, and $\langle \vec{B}_{r,SCB} \rangle$. The bottom row shows the vector components of the single pixel with the largest magnitude bounded by the SCB: $\vec{B}_{\phi,B_{\text{max}}}$, $\vec{B}_{\theta,B_{\text{max}}}$, and $\vec{B}_{r,B_{\text{max}}}$. The statistics of the extrema measurements are listed in Table 4.

Averaging the magnetic field over the area of an SCB approximates the measurements of SCBs made using MDI. The top row of Figure 7 shows a somewhat similar distribution in each component of the magnetic field to those seen in MDI – a mostly compact distribution of intensities with average intensities near zero. The zonal, meridional, and radial directions all had intensities of $2 - 3$ G compared to $-5.1$ G in MDI. Given the instrumental measurement error in HMI of $\approx 10$ G, these measurements are consistent with each other.

When examining the vector magnetic fields within an SCB, we observe apparent substructure on the scale of one or two HMI pixels. Selectively examining the magnetic extrema contained within the detected SCB boundary reveals significantly different results than averaging the magnetic intensity. The bottom row of Figure 7 shows the distribution of the magnetic vector components of these extrema. This analysis of SCB magnetic field components is clearly bifurcated into two distinct distributions in the positive and negative directions for each vector component. Table 4 lists the number and mean intensity of the magnetic extrema for each of these distributions.

In both the 6 November and 30 November events, the directional bifurcation of the magnetic vector components in the positive and negative directions are quasi-symmetric (Table 4). The number of components in the positive direction magnitude, L1 norm, within the SCB area, $B_{\text{max}} = \max(||\vec{B}_{SCB}||)$, and then measure the vector components of that pixel: $\vec{B}_{\phi,B_{\text{max}}}$, $\vec{B}_{\theta,B_{\text{max}}}$, and $\vec{B}_{r,B_{\text{max}}}$ (Figure 7 bottom).
The Origin of SCBs

Table 4. HMI vector magnetic field measurements over all SCBs for extrema within the measured SCB radius ($\vec{B}_\phi, B_{\max}$, $\vec{B}_\theta, B_{\max}$, and $\vec{B}_r, B_{\max}$).

| Event Date | Positive Direction $\vec{B}_\phi$ | $\vec{B}_\theta$ | $\vec{B}_r$ | Negative Direction $\vec{B}_\phi$ | $\vec{B}_\theta$ | $\vec{B}_r$ |
|------------|----------------------------------|-----------------|-------------|----------------------------------|-----------------|-------------|
| 6 Nov. 2010 | 134                               | 109             | 124         | 76                               | 101             | 86          |
|            | Mean $B$ (G)                      | 57              | 102         | 101                               | -54             | -101        |
| 30 Nov. 2010| 20                                | 11              | 20          | 28                               | 37              | 28          |
|            | Mean $B$ (G)                      | 70              | 90          | 59                                | -69             | -99         |

outnumber those with negative direction on 6 November, but this trend is reversed in the 30 November event. The largest magnetic intensity in both events is in the meridional direction ($\geq 90$ G), however all directions have mean magnetic intensities above 50 G. This compares to a mean magnetic field magnitude of $< 10$ G in all but one event when measured with MDI.

Combining the results of 6 and 30 November, we can define the vector components of a typical extrema within an SCB with the mean component magnitudes. This typical SCB has a zonal component ($|B_\phi|$) magnitude of 58 $\pm$ 1.4 G, a meridional component ($|B_\theta|$) magnitude of 100 $\pm$ 1.8 G, and radial component ($|B_r|$) magnitude of 92 $\pm$ 1.9 G. The overall peak magnetic magnitude of this typical SCB ($|B_{SCB}|$) is 148 $\pm$ 2.9 G.

4.2.3. Modeled Field

A PFSS model from [Schrijver and De Rosa (2003)] is used to model the coronal magnetic field above SCBs (see Section 3.3). We choose to use a PFSS model based upon the magnetic model of SCBs from [Pevtsov, Balasubramaniam, and Hock (2007)], which describes SCBs originating at the base of already existing field lines. A PFSS model is appropriate to model the magnetic field lines responsible for the location of SCBs because these field lines are in equilibrium given a pre-flare static coronal magnetic field and the footpoints of field lines are determined by the photospheric magnetic field.

The locations of SCBs are remapped onto photospheric magnetograms and used as the initialization grid for tracing the potential field lines. This technique produces a localized map of the magnetic field lines around SCBs (Figure 8). The results of this modeling for all events are shown in Table 5. An average field line derived from an SCB had a relatively consistent length of 0.20 $\pm$ 0.09 $R_\odot$, and the maximum line length averaged 0.96 $\pm$ 0.32 $R_\odot$ and never exceeded 1.45 $R_\odot$. This model does not describe the dynamics driving the creation of SCBs, but it does give valuable context to the origin and characteristics of their magnetic footpoints.

Although a PFSS model of the coronal magnetic field is not an accurate predictor for the local magnetic field lines surrounding a dynamically changing eruption for the reasons discussed in Section 3.3, some general findings can be...
Table 5. Characteristics of closed magnetic loops derived by the PFSS model for the photospheric magnetic field beneath SCBs.

| Event Date       | Mean Length ($R_{\odot}$) | Maximum Length ($R_{\odot}$) | Minimum Length ($R_{\odot}$) |
|------------------|---------------------------|------------------------------|-------------------------------|
| 19 Dec. 2002     | 0.25                      | 1.19                         | 0.009                         |
| 6 Mar. 2003      | 0.30                      | 1.44                         | 0.010                         |
| 9 Mar. 2003      | 0.13                      | 0.81                         | 0.014                         |
| 11 Jun. 2003     | 0.18                      | 0.91                         | 0.012                         |
| 29 Oct. 2003     | 0.21                      | 1.28                         | 0.005                         |
| 9 Nov. 2004      | 0.26                      | 0.86                         | 0.011                         |
| 6 May 2005       | 0.13                      | 0.94                         | 0.010                         |
| 13 May 2005      | 0.19                      | 1.09                         | 0.009                         |
| 6 Dec. 2006      | 0.39                      | 1.13                         | 0.009                         |
| 6 Nov. 2010      | 0.10                      | 0.33                         | 0.012                         |
| 30 Nov. 2010     | 0.09                      | 0.53                         | 0.011                         |

Figure 8. An example of the magnetic field lines above SCBs modeled using a PFSS approach from 19 December 2002. The green lines are positive open field lines and closed lines are plotted in white above an MDI magnetogram. One footpoint of each modeled loop is rooted in an SCB. The SCBs visible in this image are indicated with a yellow dot.

made from this model. First, over 95% of the lines modeled were closed, and of the closed lines, none reached beyond 1.45 $R_{\odot}$. Second, there is no correlation between field line length and intensity or duration of SCB. This lack of correlation means that the strength of the magnetic field is not driving the intensity or duration of the brightening. Third, only a loose correlation is observed between the distance of the SCB from the flare center and field line length. No long field lines are found close to the flare center, and short field lines are most likely to be found near the flare.
5. Discussion and Implications

Tracking flare kernels through the evolution of an erupting flare is an effective way to characterize the associated evolving active region in spatially resolved images. The sum of these kernels reconstructs the profile of the associated X-ray intensity curve of the flare and individual kernels that persist through a majority of the eruption. The flare kernels dissect the flare into its smallest visibly resolvable components in the H$\alpha$ images. It is not possible to surmise that a single kernel is tracking a specific flare loop in this study. A thorough investigation and discussion of the dynamics of flares and flare kernels can be found in a forthcoming work.

SCBs are found to be a specific case of chromospheric compact brightenings that occur in conjunction with flares. The distinct nature of SCBs from other brightenings in H$\alpha$ arises from their impulsive brightening and decay, rapid propagation and dispersal away from the flare center. Despite the observed propagation, the heated plasma in tracked SCB kernels does not physically progress in any coherent direction. SCBs in aggregate often precede the H$\alpha$ flare peak and have evolutions that are distinct from the GOES soft X-ray emission, which is a proxy for the thermal component of the flare emission. The temporal coincidence yet separation between flare and SCB evolution suggests that SCBs have an origin that is separate from the H$\alpha$ flare but is driven by a triggering mechanism that is causally connected to the host flare.

The most common photospheric magnetic field intensity of SCBs is near 0 G when measured in MDI, yet does not necessarily disprove the prevailing unipolarity hypothesis. The weak relationship between SCBs and measured magnetic intensity is most likely to be the result of the quality of the MDI magnetograms. MDI magnetograms used in this study have half the resolution of the H$\alpha$ images, meaning that four MDI pixels completely covers the entire area of a typical SCB. Also, since the MDI magnetograms only measure LOS magnetic field, the locations of the SCBs on the solar disk (see Table 1) have a strong influence on the measured magnetic intensity. The closer the measurements are to the limb, the more tangential the magnetic field measured in the magnetogram and thus closer to zero. A highly inclined magnetic field might also skew measurements, since the magnetic polarity directly beneath the SCB would then not represent the strength of the field line connecting the photosphere to the chromosphere.

When measuring the vector magnetic components using HMI data, a stronger signal appears (Figure 6). If the HMI magnetic field is averaged over the SCB area, the results are similar to MDI with mean intensities of the SCB population near zero. When only the extrema are selected within the geometric boundaries of the SCB, two distinct populations emerge in the positive and negative directions in each vector component (Figure 7). The extrema were selected from the strongest measured LOS magnitude of HMI pixels within an SCB boundary without consideration of the vector components of the field. By calculating their skewness and kurtosis, we show the extrema statistical significance. We demonstrated in Table 4 the non-triviality that each vector component of those extrema exhibits a bifurcated population. These directional populations are biased in the positive direction on 6 November, but this trend is reversed in the 30 November event.
The bifurcated populations of magnetic components observed beneath SCBs imply that SCBs are magnetically anchored in the photosphere, i.e. they are not purely atmospheric phenomena. This finding does not disagree with the prevailing unipolarity hypothesis. Visually distinct magnetic features are also routinely observed within the boundary of a given SCB, which suggests that the magnetic footpoint of an SCB in the photosphere is significantly smaller than the area of the Hα chromospheric brightening. Higher resolution Hα imaging of SCBs is needed to more fully investigate the apparent size discrepancy between the photospheric and chromospheric measurements.

There is a lack of any significant correlation between the distance at which SCBs appear and modeled magnetic field line length, suggesting that the heuristic model presented by Kirk et al. (2012b) is most likely an oversimplified schematic of the eruption. This heuristic model postulates that SCBs arise from a series of nested quiescent coronal loops that are disturbed when the flare erupts. However, a majority of magnetically modeled SCBs have field lines that exist between 0.1 and 0.3 $R_\odot$ above the photosphere, indicating that the mechanism for driving SCBs is most likely in the lower corona.

Figure 9 illustrates our current understanding of the temporal progression of SCBs and eruption of the associated flare. Panel 1 depicts a potential-field solution to the photospheric magnetogram of the flaring region, such as performed by the PFSS model. The flaring region is shown in the center as well as a quadrupolar active region and three small dipolar field configurations.

Panel 2 in Figure 9 shows the initial destabilization of the flaring region and the accompanying magnetic field lines expanding into the localized area and the reaction of the quadrupolar region. The red “X” indicates the location where reconnection takes place between the flare magnetic field and the quadrupolar active region.

Panel 3 in Figure 9 shows the flaring region before flare reconnection but after the appearance of the first SCBs. Loops marked A and B are newly reconnected from the x-point in panel 2 and the SCBs observed as a result of plasma accelerated by this reconnection are shown by the green diffraction spikes. The loops marked as A are now overarching the entire erupting region and confine the expanding eruption. The red “X” denotes where the main flare reconnection takes place.

Panel 4 in Figure 9 shows the flare arcade loops as well as the erupting flux rope, both in orange. The observed flare ribbons are indicated with yellow diffraction spikes. As the overarching magnetic field lines (A) are further stressed, they become unstable themselves and reconnect (not shown) to magnetic footpoints further away from the flare. These newly connected lines, marked as lines C and D, also produce observable SCBs indicated by green diffraction spikes. As the flare eruption evolves it also releases some magnetic stress imposed on the quadrupolar region, allowing a more potential field to reemerge as indicated by line E.

Panel 5 in Figure 9 shows the flux rope eruption moving beyond the local region depicted and the dipolar and quadrupolar regions relaxing into a potential field configuration. Notice that one dipolar region remained unchanged throughout the eruption. This is due to the physical geometry of the eruption itself.
Figure 9. A heuristic interpretation of the temporal progression of SCBs and the associated flare. Magnetic loops, shown in blue, connect negative and positive polarity photospheric footpoints in the photosphere, shown in black and white. Newly reconnected magnetic field lines are highlighted in orange. A red “X” indicates sites of magnetic reconnection and diffraction spikes in green or yellow indicate regions of observed intensity enhancement of SCBs or flare ribbons respectively.

Two ribbon flares have an elongated axis that makes it favorable for field lines to connect to regions tangentially aligned with this axis. Regions perpendicular to this flare axis are more resilient to reconnection with the flare arcade and thus less prone to SCBs.

The findings presented so far all constrain the triggering mechanism for SCBs. Given the likely presence of a CME when SCBs are observed, we can postulate
that both come from a common physical origin in the lower corona. Directly
driven models of CME release are inconsistent with the measurements of SCBs
made here. In a thermal blast model (e.g. Dryer 1982), thermal pressure is the
driver of a CME. In that case, we would expect to see a correlation between the
strength and propagation velocity of SCBs to scale with the energy release of
flares. There is no such connection between the energy released in the flare and
propagation speed of SCBs.

In the CME breakout model, Antiochos, DeVore, and Klimchuk (1999) pos-
tulate that the energy stored in a closed and sheered arcade plays a crucial role
in determining when a CME eruption will occur. In this model, the reconnection
event that triggers a CME is a low-energy event located above the erupting
arcade. This low-energy pre-CME reconnection event at first glance seems like
it could be the triggering mechanism for SCBs since SCBs are the result of
accelerated particles impacting the chromosphere (Kirk et al. 2014) and often
occur before the onset of the primary flare emission. If this pre-CME recon-
nection described SCBs, we would expect to observe a correlation between the
measured physical parameters of SCBs (e.g. number of SCBs and H\alpha intensity)
and the physical characteristics of the associated CME (e.g. velocity and mass).
For example, in this scenario if a high speed CME were released, there must be
either a high energy pre-CME reconnection or many smaller reconnections and
we would expect to observe either more SCBs or SCBs with higher H\alpha intensities.

We do not observe any correlation between the plasma dynamics of SCBs and
the measured properties of the associated CME. This lack of correlation implies
that SCBs are not a direct product of the driver of CME release.

6. Conclusions

Sequential coronal brightenings (SCBs) are a type of localized chromospheric
heating and ablation due to impacting coronal plasma (Kirk 2013; Kirk et al.
2014). SCBs are unlike flare ribbons in that they are a secondary effect of solar
eruptions. Using an automated detection and tracking algorithm, we can now
readdress the three questions asked at the outset of this investigation. (1) Is there
a relationship between the properties of the host flare and associated SCBs? (2)
Is there a consistent photospheric magnetic field component to SCBs? (3) Can
a potential coronal field model help explain the other SCB measurements?

Addressing the first question, SCBs originate in quiescent coronal magnetic
loops above a chromospheric flare that are forcibly disturbed in the course of
the flare eruption. As these coronal tethers reconfigure, trapped plasma is now
free to cascade into the chromosphere causing SCBs. This model is affirmed
by the finding that 82% (9 out of 11) of SCB events in this study accompany
subsequent visible CMEs, also validating the conclusions of Balasubramaniam
et al. (2006). The corona and chromosphere are visibly disturbed by each other
in the eruption process of a filament or flare and the progressive trains of SCBs
observed propagating away from the flare with velocities in two distinct groups: a
slow group with speeds between 35 and 85 km s\(^{-1}\), and a fast group propagating
at speeds > 150 km s\(^{-1}\). These groups of SCBs are evidence of the pre-flare
surrounding magnetic topology rather than the flare itself.
SCBs are more closely related to the release of an associated CME rather than the flare itself. Viewing SCBs as a product of CME formation and eruption explains why flares releasing vastly different energies (from no X-ray signature to an X10.0 flare) have SCBs with similar physical traits. Since SCBs can first appear before the onset of Hα emission in a flare, during the impulsive phase, or after the peak intensity, an associated CME is most likely to be the process driving the appearance of SCBs rather than flare reconnection. Chromospheric observations of flare and filament eruptions (such as with ISOON) can give an indication of an emerging CME up to a couple hours before the CME is detected with a coronagraph.

The second question asked by this study relates to the magnetic flux of SCBs. Several other works on SCBs state that they should be unipolar (e.g. Balasubramaniam et al., 2006; Kirk et al., 2012a). This work found a slight magnetic bias when measured with MDI. When measuring magnetic vector magnetic field components of SCBs using HMI, a significant signal is observed. Each vector magnetic component in both events with HMI coverage showed a distinctly nonzero result in either the positive or negative direction. These findings suggest a magnetic footpoint of SCBs in the photosphere with a diameter significantly smaller than that in the chromospheric brightening with a peak intensity of 148 ± 2.9 G.

Lastly, we explored a potential field model of SCBs. A potential model seems illogical at first, since SCBs are dynamic features which are most certainly non-potential. But because SCBs are more indicative of the quiescent pre-flare environment than the flare itself, a potential model makes sense as a first-order estimate as to where SCBs form. A PFSS model suggests that the origin of SCBs lies in the lower corona, at heights around 0.1 $R_\odot$ above the solar surface.

This research finds statistically significant magnetic substructure within the Hα boundary of SCBs. The potential field extrapolation of the magnetic field within SCBs shows magnetic field lines extending into the low corona. Both of these findings combined, point to the conclusion that a single SCB represents a magnetic footpoint of a coronal magnetic loop, which supports the hypothesis that SCBs are unipolar. It is conceivable that future observations of SCBs will reveal a more complicated substructure or more subtle evolution.

Lasting only a few minutes, SCBs are fleeting indicators of the solar flare environment at the time of flare eruption. Unfortunately due to their small physical size, low intensity, and short lifetime, the physical description of SCBs is incomplete and hyperspectral imagery of this phenomenon is required for a complete picture. In all previous studies, SCBs are identified by their Doppler intensity profile in Hα images. The ISOON telescope was the only full disk solar imager that regularly recorded full-disk off-band images in the Hα line with suitable resolution to capture SCBs. Unfortunately this telescope was decommissioned in 2011 and has not been replaced.

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