Large scale solar chromospheric eruptive activity - a signature of magnetic reconnection

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Abstract. A new class of large-scale solar chromospheric eruptive activity, sequential chromospheric brightenings (SCBs), has been reported by Balasubramaniam et al. (2005). SCBs are chromospheric network points (outside of active regions) that sequentially brighten over a narrow path of chromospheric network points. SCBs appear as single or multiple trains of brightenings, the underlying magnetic poles of each train having the same (negative or positive) polarity. SCBs may be associated with the following phenomena: solar flares, filament eruptions, CMEs, disappearing transequatorial loops, Moreton and EIT waves. We present an understanding of SCBs and their place in respect to these related eruptive phenomena.

Index Terms. Chromosphere, coronal mass ejections, magnetic reconnection, solar eruptions.

1. Introduction

Sequential chromospheric brightenings (SCBs) are a series of spatially separated network points that brighten in sequence, giving the appearance of a progressive traveling wave. SCBs appear as single or multiple trains of brightenings in conjunction with large-scale eruptive activity in the chromosphere and/or corona. The brightenings appear as a propagating disturbance, over a narrow path of chromospheric network points, seen in temporal sequence of full-disk Hα images

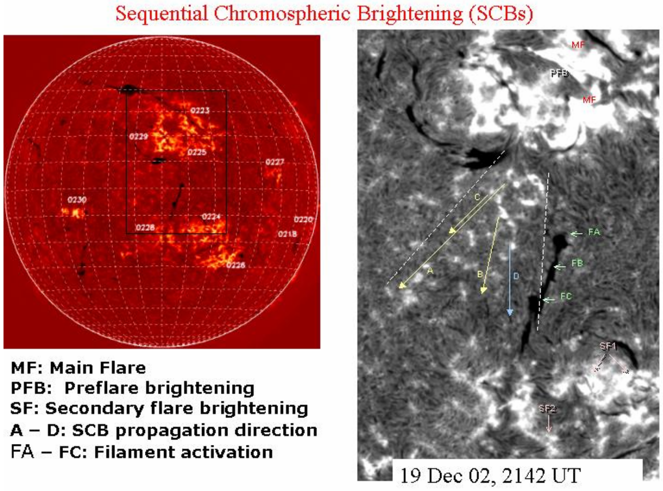


Fig. 1. Representation of the path for four SCBs, on 2005 December 19, between 20:38-21:00 UT. The speeds of four propagating disturbances (A - D) are 817, 584, 601 and 690 km $s^{-1,}$ respectively.

SCBs are spatially correlated with underlying magnetic poles of same (negative or positive) polarity. Closely situated opposite polarities are usually unaffected. SCBs may be associated with the following phenomena: solar flares, filament eruptions, CMEs, disappearing transequatorial loops, Moreton waves, and EIT blast waves. We refer the reader to a paper by Balasubramaniam et al. (2005), for a detailed description of SCBs. Fig.1 illustrates the SCBs. In this paper, we discuss the nature of SCBs based on a statistical survey (Sec. 3) and show a case study of an erupting region (Sec. 4-5) to explain the underlying causes of activity (Sec. 6).

2. Data sources

The following data sources were used to study SCBs

- Hα (6562.8 Å) line-core and wing (± 0.4 Å) images: Full disk images observed using USAF/Optical Solar Patrol Network, O-SPAN at NSO (formerly known as ISOON (Neidig et al 1998) at 1-minute cadence and 1.1 arcsecond/pixel resolution; http://nsosp.nso.edu/isoon/
- TRACE 171 Å data (Tarbell et al., 1994; Handy et al., 1999) at 0.5 arcseconds/pixel http://trace.lmsal.com/Data/trace_cat.html
- SOHO/MDI full-disk magnetograms with 1.98 arcsecond/pixel resolution and 90 minutes cadence. (Scherrer et al., 1995);

  http://soi.stanford.edu/production/time_range.htm.
- NOAA/GOES List of flares with start time, end time, time of maximum, location on solar disk, optical and X-ray importance.

  http://www.ngdc.noaa.gov/stp/SOLAR/ftpsolarflares.htm
- SOHO/LASCO CME Catalog: List of CMEs with C2

start time, speed, central angle. Also included in that catalogue are TRACE 195 Å, C2, and C3 movies. (Yashiro et al., 2004);

http://cdaw.gsfc.nasa.gov/CME_list**.**

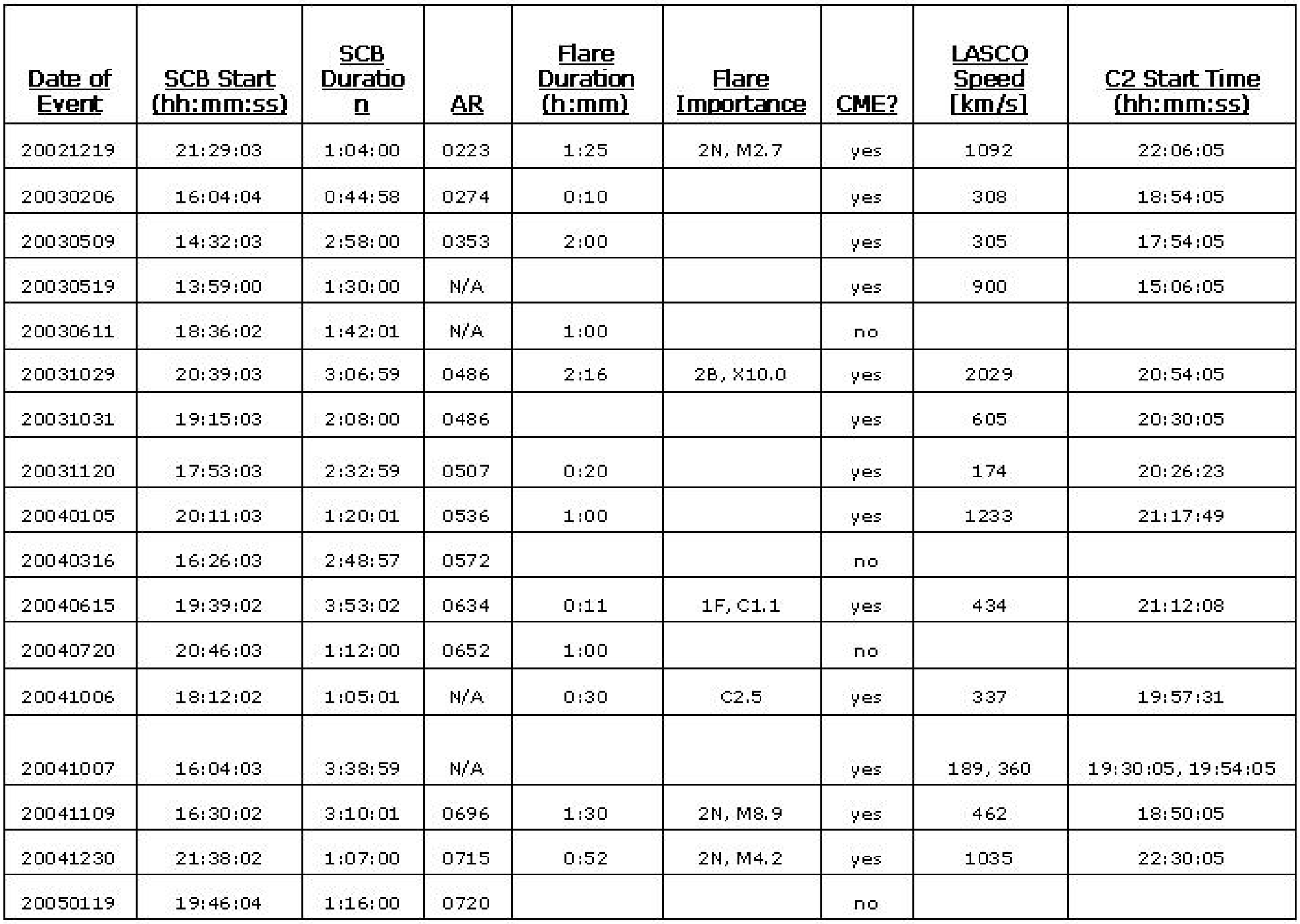
- RHESSI List of flares: List of flares complementing the NOAA/GOES list. Lin et al., 2004); http://hesperia.gsfc.nasa.gov/rhessidatacenter/

3. Survey of SCBs

We surveyed all available O-SPAN observations, a total of 443 days (2002 December 19 - 2005 July 29). For each day of O-SPAN data, we made a sequential movie of the 1-minute cadence images at Hα line-center, and identified and recorded, wherever possible, SCBs, flares, and filament eruptions. For flares we recoded the times and strength of from the corresponding NOAA/GOES or RHESSI data. In recording the flares, we considered flares that were stronger than optical importance S or X-ray importance B were considered. The presence of CMEs was deduced from the LASCO CME catalogue.

During this period O-SPAN detected 324 flares that corresponds to only 4% of flares recorded by NOAA/GOES. About 15% of all LASCO CMEs occurred within daily periods of O-SPAN observations. A total of 40 ribboned-flares were seen, as were 92 filament eruptions or partial filament dissipation. A total of 17 SCBs was detected. While each SCB is unique, they all share certain characteristics. First, SCBs are large-scale events spreading over areas much larger than single active regions. Second, they tend to have a sufficiently long duration to be clearly identified in the movies. The average length of a SCB event in Hα is just over two hours.

Table 1. Statistics of the 17 SCBs Observed During the 443 Days of ISOON Data.



Date of Event	SCB Start (hh:mm:ss)	SCB Duration	AR	Flare Duration (h:mm)	Flare Importance	CME?	LASCO Speed [km/s]	C2 Start Time (hh:mm:ss)
20021219	21:29:03	1:04:00	0223	1:25	2N, M2.7	yes	1092	22:06:05
20030206	16:04:04	0:44:58	0274	0:10		yes	308	18:54:05
20030509	14:32:03	2:58:00	0353	2:00		yes	305	17:54:05
20030519	13:59:00	1:30:00	N/A			yes	900	15:06:05
20030611	18:36:02	1:42:01	N/A	1:00		no		
20031029	20:39:03	3:06:59	0486	2:16	2B, X10.0	yes	2029	20:54:05
20031031	19:15:03	2:08:00	0486			yes	605	20:30:05
20031120	17:53:03	2:32:59	0507	0:20		yes	174	20:26:23
20040105	20:11:03	1:20:01	0536	1:00		yes	1233	21:17:49
20040316	16:26:03	2:48:57	0572			no		
20040615	19:39:02	3:53:02	0634	0:11	1F, C1.1	yes	434	21:12:08
20040720	20:46:03	1:12:00	0652	1:00		no		
20041006	18:12:02	1:05:01	N/A	0:30	C2.5	yes	337	19:57:31
20041007	16:04:03	3:38:59	N/A			yes	189, 360	19:30:05, 19:54:05
20041109	16:30:02	3:10:01	0696	1:30	2N, M8.9	yes	462	18:50:05
20041230	21:38:02	1:07:00	0715	0:52	2N, M4.2	yes	1035	22:30:05
20050119	19:46:04	1:16:00	0720			no		

Viewing the available TRACE 195 Å movies at the time of SCBs, all but one SCB event showed outer coronal loops expanding and a sudden formation of secondary coronal loops some of which also begin to extend outward. The footpoints of these secondary loops are co-spatial with SCBs. For the event of 2004 March 16, about NOAA AR 10572, the SCB appears not to be associated with this type of coronal reconnection. Instead, both O-SPAN Hα and TRACE 195 Å images show a ``V" of chromospheric footpoints moving apart. In Fig. 2 we show a mosaic of O-SPAN images showing the progression of this SCB, which is associated with a filament disappearance, but the explicit absence of a flare.

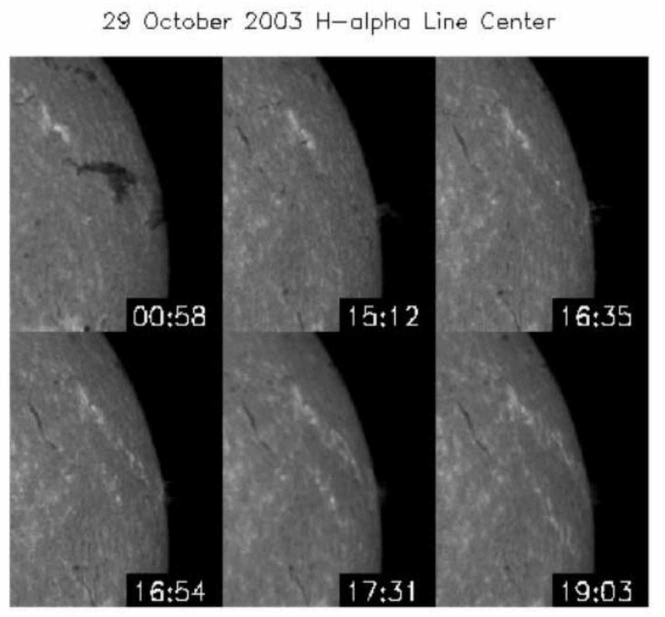


Fig. 2. Progression of an SCB event with a filament eruption, but without a flare, on 2004 March 16.

A particularly good example of SCBs is that of 2003 October 29 starting about NOAA AR 10486. This event is associated with a long duration X10.0 X-ray flare. Here there are two SCBs, one propagating northeast, and the other towards the SE direction. These events are short lived lasting about 10 minutes. The SCBs also are associated with a filament eruption, Moreton waves, and halo-CMEs. This event is the subject of a detailed study in an upcoming paper, elsewhere.

4. Statistics summary

We found only 17 examples of SCBs between December 2002 and March 2005 (Table 1), which may correspond to about 4-15% of all SCBs events. Fig. 5 shows the percentage of hours, days, flares and CMEs observed as a function of time. Also plotted is the number of SCB events seen. There appears to be no bias in the sampling of O-SPAN data.

- There is surprisingly small number of SCB events (17) in a 3.5-year period.
- There is a 100% association of SCBs with filament disappearance or some changes in filament structure (partial filament eruption).
- 71% (12/17) of SCBs are related to CMEs and, 29% (5/17) have no CME association. In most cases the timing of an associated CME is 30 minutes to several hours after the start of the SCB. Since a fraction of SCBs were not accompanied by a CME, it is possible that either the CME was too faint to be seen in LASCO or LASCO observations were just not available during these periods.
- 65% (11/17) of SCBs are related to flares, about 35% are unrelated to flares. 50% (9/17) of SCBs had a flare whose duration ranged from 0 - 30 minutes. 24% (4/17) of SCBs had a flare whose duration was between 30 - 60 minutes. The rest (25%) were long duration events lasting well over an hour (see Fig. 4).

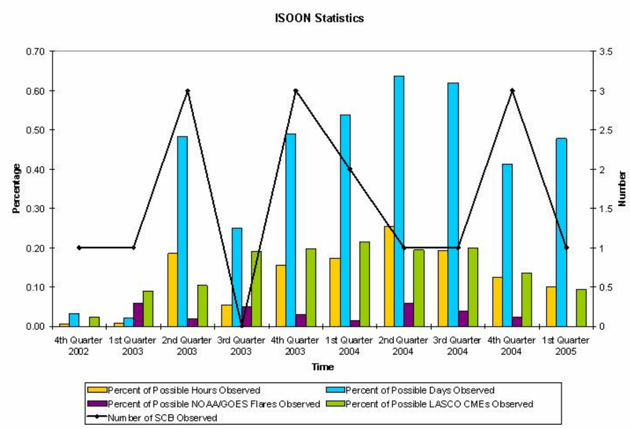


Fig. 3. Percentage of possible ISOON observations, with the corresponding number of SCB events.

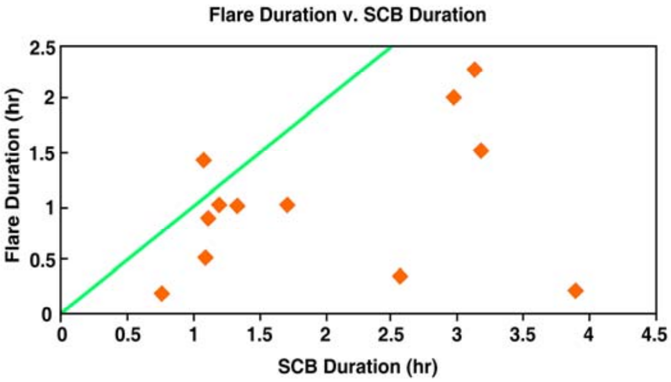


Fig. 4. SCBs when associated and compared with flares, are longer lived. Perhaps SCBs are not a direct consequence of flares.

SCBs are relatively rare events; they are associated with filament eruption, and short-duration flares. The fact that they tend to appear in conjunction with filament eruptions and short duration flares suggests that SCBs may be associated with slow reconnection events. When the reconnection takes place very rapidly, we do not see SCBs. When associated with CMEs, SCBs precede them significantly. Hence, SCBs can be used to statistically predict CMEs.

5. SCB case study

From a survey of SCBs, as explained in the previous sections, we identified a long-duration eruptive (LDE) event on 2005 May 6, near active region NOAA 10758. Figs. 5-6 illustrate the event. A C8.5 X-ray flare was recorded by GOES with a flare start at 16:03 UT, peak at 17:05 UT.

Fig. 6 shows the progression of the long duration flare, expansion of the flare ribbons and the associated SCBs. The event lasts for about 6 hours.

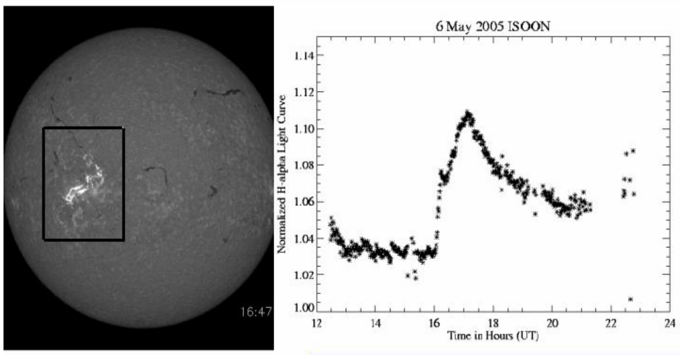


Fig. 5. An LDE on 2005 May 6 near NOAA 10758.

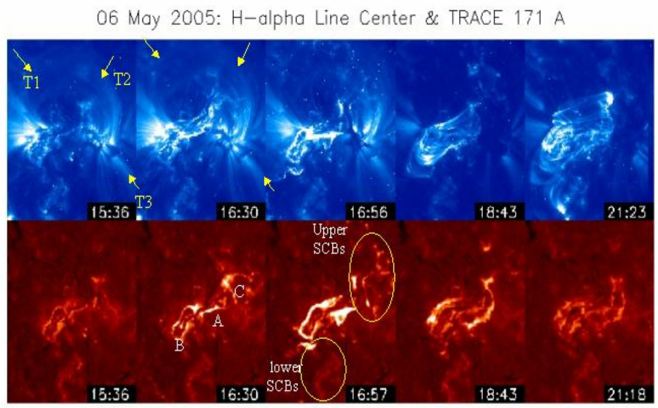


Fig. 6. The series of expanding activity, with flares, filament eruptions and SCBs. A mosaic of TRACE 171 Å and Hα line-center images showing the progression of the SCB event. Note the ballooning of the outer coronal loops marked by arrows, formation of post-flare loops, and secondary loops at locations of SCBs.

The following is the sequence of the chromospheric activity (see also Fig. 6):

- 16:05 UT -- Filament (SE to NW; above location joining A-B) erupts.
- 16:06 UT -- Main two-ribbon flare A, erupts, and moves away from filament.
- 16:08 UT -- Footpoints north of the filament begin to brighten. Upper SCBs progress.
- 16:12 UT -- Lower SCB's forms to the southeast of filament.
- 16:33 UT -- Two-ribbon flare, C, starts.
- 16:42 UT -- Two-ribbon flare, B, starts.
- 16:47 UT -- SCB progression wipes out filament lying to the north of the active region
- 17:00 UT -- Two-ribbon flare terminates motion.
- 17:01 UT -- Lower SCBs dim.
- 17:08 UT -- footpoints north of the filament maximizes in intensity, and then begins to dim.
- 17:24 UT -- SCB progression wipes out filament second filament.
- 17:57 UT -- Two-ribbon flare, B, terminates motion.
- 18:05 UT -- Two-ribbon flare, A, terminates motion.

TRACE 171 Å images show the overlying coronal loop structure (see Fig. 1). Prior to the onset of the flare (15:36 UT) large overlying coronal loops connecting across regions slowly expand and appear to erupt. The overlying coronal loops (marked T1, T2) connecting the two bright coronal regions (left and right in each frame) are about 250 arcseconds apart. A second large-scale loop, marked by T3 connects the region on the right to another at the south, 300 arcseconds away. As the filament erupts, these overarching loops appear to balloon and expand. This could be due to loops being physically pushed outward or it could be due to brightening of sequential loops**.**

At 16:56 UT, all three ribbon flares are visible as are the SCB footpoints. As *ribbon A* spreads outward, post-flare inner coronal loops are seen connecting the eastern and western ribbons. No such connection is seen between the ribbons in *ribbon B* and in *ribbon C*. In fact the eastern ribbon of *ribbon C* appears to be a continuation of the western ribbon of ribbon A. The outer coronal loops connect the eastern ribbon of *ribbon A* and the western ribbon of *ribbon C*. No coronal loops are visible at this time originating from *ribbon B.*

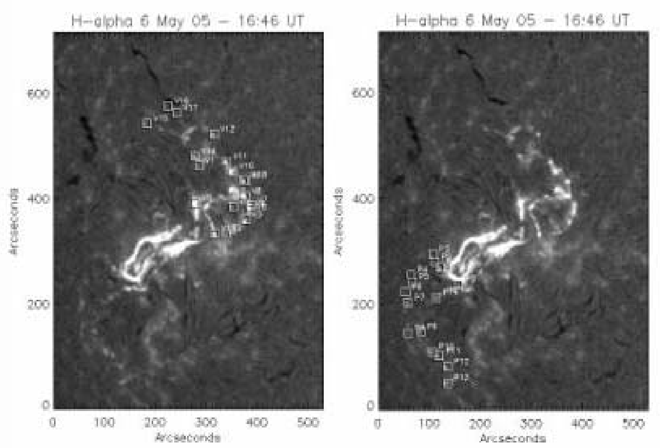


Fig. 7. The upper and lower SCBs are marked for identification. The ``speeds" of SCB propagation are measured using times at which the different network points are brightened.

At 17:23 UT, the eastern ribbon of *ribbon C*, western ribbon of *ribbon A* moves westward. Coronal loops connect the southern ribbon of *ribbon B* with the eastern ribbon of *ribbon A*. The outer coronal loops continue to push outward. From 17:23 UT to 22:44 UT (end of images), both the inner and outer coronal loops continue to expand. The western footpoints move to the west. The inner loops terminate at the western ribbon of *ribbon A* while the outer loops terminate at the western ribbon of *ribbon C*, no longer visible in Hα. The outer loops move away faster than the inner loops. This gives the appearance that northern portion of the western ribbon of *ribbon A* (also called the eastern ribbon of *ribbon C*) and the western ribbon of *ribbon* C are a ribbon flare. LASCO reported a partial halo CME event that was first seen in C2 at 17:28 UT above the southeastern limb. This event was first seen in C3 at 17:42 UT. The EIT 195 Å images confirm that this CME originates in AR 10758. The linear fit speed is 1180 km s^{-1} and the acceleration is -38.1ms^{-2}.

Both lower and upper SCBs appear to originate from a narrow cone at either end of the filament and progress following the topology of the magnetic fields. The chromospheric bright-points do not physically move with the disturbance associated with the filament eruption. However, the brightenings occur sequentially. The speed of the disturbance can be determined by calculating when the intensity of each bright-point peaks.

Both the upper and lower SCBs have velocities between 10 and 50 km $s^{-1.}$ The southern series of SCBs is fainter in Hα than the northern series. The magnetograms reveal that the flux in the southern region is weaker than the flux in the northern regions. The SCBs (at the chromospheric level) brighten earlier, by several (2 - 5) minutes, when compared with TRACE 171 Å images. The SCBs are at the footpoints of secondary coronal loops.

6. Photospheric magnetic fields

The magnetic field structure seen in the MDI magnetograms shows a complex arrangement of negative and positive flux regions. The upper SCBs all have negative polarity while the lower SCBs have positive polarity. Though this region is complex, it is relatively stable. Three small flux emergence occur at 15:41 UT, 15:42 UT and 18:30 UT, uncorrelated with any changes in Hα. Proper motion of network flux elements were tracked from 13:00 UT to 22:59 UT. Flux regions associated with SCB move away from the filament. Flux regions associated with the western ribbon of *ribbon A* and eastern ribbon of ribbon *C* also move away from the filament.

7. Conclusions

From the detailed study of the event on 6 May 2005, SCBs appear to be complicated events involving activity in both the chromosphere and the corona. We conjecture the following model. An un-established source of instability causes the ejection of overarching outer coronal loops. A flare results, following which filament eruption precedes the formation of post-flare loops. As the filament erupts newer magnetic connections are established via reconnection, following to the global instability. High-energy electrons spiral down along field lines (along the loops) to the denser chromospheric targets where they heat up resulting in SCBs. The heating causes the chromospheric volume to evaporate along the field lines lighting up the coronal loops, seen in TRACE 171 Å. The erupting outer coronal loops and the filaments form the CME and the particle streams. A cartoon model representation of the SCBs, flares, and the associated loop eruptions are shown in Fig. 8.

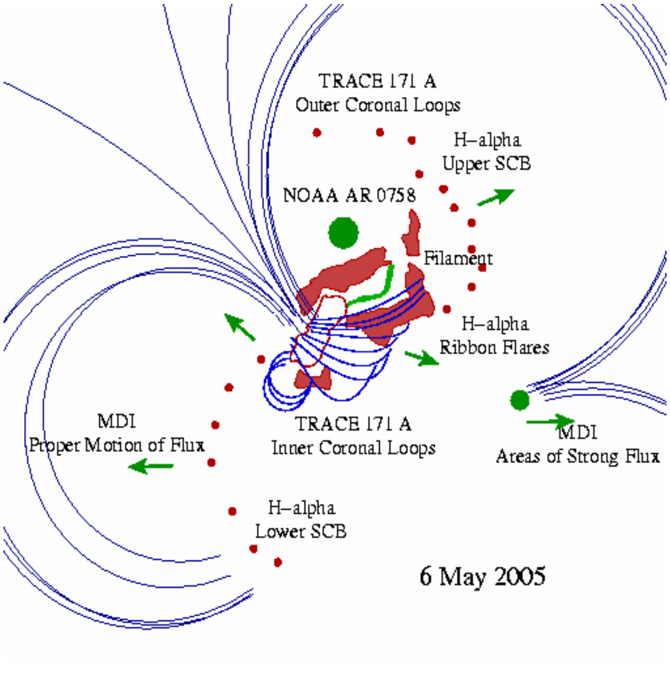


Fig. 8. A model of the SCB event of 2005 May 6.

SCBs are chromospheric signatures of coronal reconnection.

They are different phenomena from Moreton waves, EIT blast waves. They

–Are early signatures of magnetic reconnection.

–Precede Moreton & EIT waves.

–Are early signatures of chromospheric evaporation - appear prior to bright coronal loops (TRACE).

SCBs are more likely to be associated with a short duration flare. Rapid reconnection is likely to result in sudden acceleration of particles to chromospheric foot-points (SCBs). They are always associated with a filament eruption or disruption. Their association with CMEs is slightly weaker, perhaps due to failed filament eruptions and undetected CMEs. The next step in understanding SCBs is to model their behavior.

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References

K. S. Balasubramaniam et al., "Sequential Chromospheric Brightenings beneath a Transequatorial Halo Coronal Mass Ejection,*” Astrophys. J.*, vol. 630, pp. 1160-1167, 2005.

R. P. Lin et al., "The Reuven Ramaty high-energy solar spectroscopic imager (RHESSI) mission" in *Telescopes and Instrumentation for Solar Astrophysics.* vol. 5171, S. Fineschi and M. A. Gummin, Eds. Proc. SPIE, 2004, pp. 38-52.

D. F. Neidig et al., "The USAF Improved Solar Observing Optical Network (ISOON) and its Impact on Solar Synoptic Data Bases" in *Synoptic Solar Physics.* vol. 140, K. S. Balasubramaniam; Jack Harvey; and D. Rabin, Eds. ASP Conf. Ser., 1998, p. 519.

P. H. Scherrer et al., "The Solar Oscillations Investigation - Michelson Doppler Imager" *Solar Phys*., vol. 162, pp. 129-188, 1995.

T. Tarbell et al., "The transition region and coronal explorer (TRACE)" in *Solar Dynamic Phenomena and Solar Wind Consequences,* J. J. Hunt, Ed. ESA SP-373, 1994, p.375.

S. Yashiro et al. "A catalog of white light coronal mass ejections observed by the SOHO spacecraft", *J. Geophys. Res*., vol. 109, A07105, 2004.