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**AUTOMATIC RECOGNITION OF SOLAR  
FEATURES FOR DEVELOPING DATA DRIVEN  
PREDICTION MODELS OF SOLAR ACTIVITY AND  
SPACE WEATHER**

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**Final Report**

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<b>14. ABSTRACT</b> Space weather is driven by solar activity and is an important component of U.S. Department of Defense (DoD) research. It affects both civilian and commercial assets in space and on the ground. Severe changes in space weather can damage or cause failure of communication and navigation systems of interest to the DoD, as well as civilian and commercial entities. Researchers in the solar community need a method of quickly characterizing solar activity to feed data-driven models that forecast eruptive events and space weather for the DoD ground and space systems. This work addresses this need by using several observational databases to develop and utilize algorithms to (a) automatically track and recognize features that precede eruptive solar events; (b) parametrize physical properties for each of these regions; and (c) create dynamic, data-driven models of solar activity that will capture the temporal evolution of these features and quantify their importance in the eruption of flares and coronal mass ejections.					
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# 1 Introduction

The scope of this project is to analyze various targeted data sets, particularly chromospheric H $\alpha$  images, to understand the complicated physics of solar flares. In particular, the proposed research is to gain a better understanding of the properties of Sequential Chromospheric Brightenings (SCBs) [1] and to develop algorithms to (a) automatically track and recognize active solar regions, (b) to parametrize the physical properties of each of these regions at the various observed layers, and (c) to develop dynamic, data-driven models of solar activity that will capture the temporal evolution of these features and understand their importance in the eruption of flares and coronal mass ejections.

The funds for this project have been used to support a graduate student, Michael Kirk, in the Astronomy Department at New Mexico State University (NMSU). He is currently pursuing his doctoral degree, having obtained his M.S. in Astronomy in April 2011. His expected doctoral defense is December 2012.

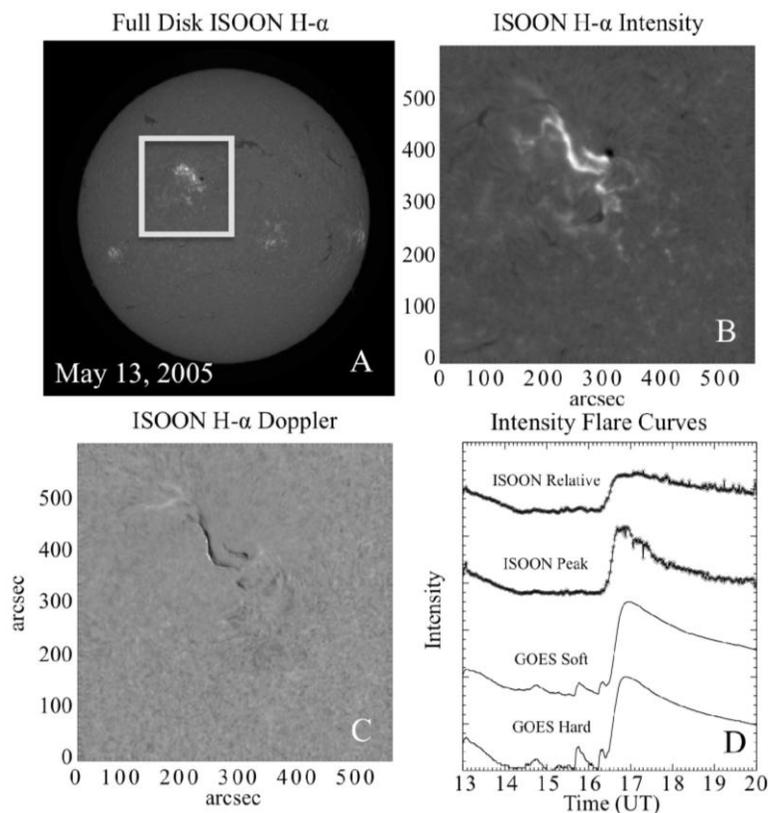
## 2 Background

The solar chromosphere exhibits three different classes of small-scale intensity brightenings: flare, plage, and compact brightenings. Although each is characterized by an enhanced temporal H $\alpha$  brightness relative to a background quiet Sun, they each have distinct physical processes governing their spatial and temporal evolution. Typically, brightenings have been identified and characterized manually from a single data source. However in order to form a better understanding of the underlying dynamics, data from multiple sources must be utilized and numerous similar features must be statistically analyzed. This work focuses on flare brightenings and associated compact brightenings called sequential chromospheric brightenings (SCBs). SCBs were first observed in 2005 and appear as a series of spatially separated points that brighten in sequence [1]. SCBs are observed as multiple trains of brightenings in association with a large-scale eruption in the chromosphere or corona and are interpreted as progressive propagating disturbances. The loci of brightenings emerge predominantly along the axis of the flare ribbons. SCBs are correlated with the dynamics which cause solar flares, coronal restructuring of magnetic fields, halo CMEs, EIT waves, and chromospheric sympathetic flaring.

## 3 Methods, Assumptions, and Procedures

This work presents a new description of the dynamical properties of SCBs resulting from applying a new automated method [2] of identifying and tracking SCBs and associated flare ribbons. This tracking technique differs from previous flare tracking algorithms in that it identifies and tracks spatial and temporal subsections of the flare and all related brightenings from pre-flare stage, through the impulsive brightening stage, and into their decay. Such an automated measurement allows for tracking dynamical changes in intensity, position, and derived Doppler velocities of each individual subsection. The tracking algorithm is also adapted to follow the temporal evolution of ephemeral SCBs that appear with the flare.

In this study we use chromospheric H $\alpha$  images from the USAF's Improved Solar Observing Optical Network (ISOON) prototype telescope to study flare ribbons and SCBs [3]. ISOON is an automated telescope producing 20482048 pixel full-disk images at a one-minute cadence. Each image has a 1.1 arc-second spatial sampling, is normalized to the quiet Sun, and corrected for atmospheric refraction. An example snapshot of these data during a flaring event is shown in Figure 1. Panel A shows an example of a calibrated ISOON image with the region of interest (ROI) highlighted. Panel B is the ROI after preprocessing. Panel C is a Doppler measure of the same ROI as panel B. The Doppler velocity image is created out of ISOON off-band images and the velocity ranges from  $-26.6$  to  $21.5$  km s $^{-1}$  from black to white. Panel D shows intensity curves in H $\alpha$  and X-ray over the time period of interest.



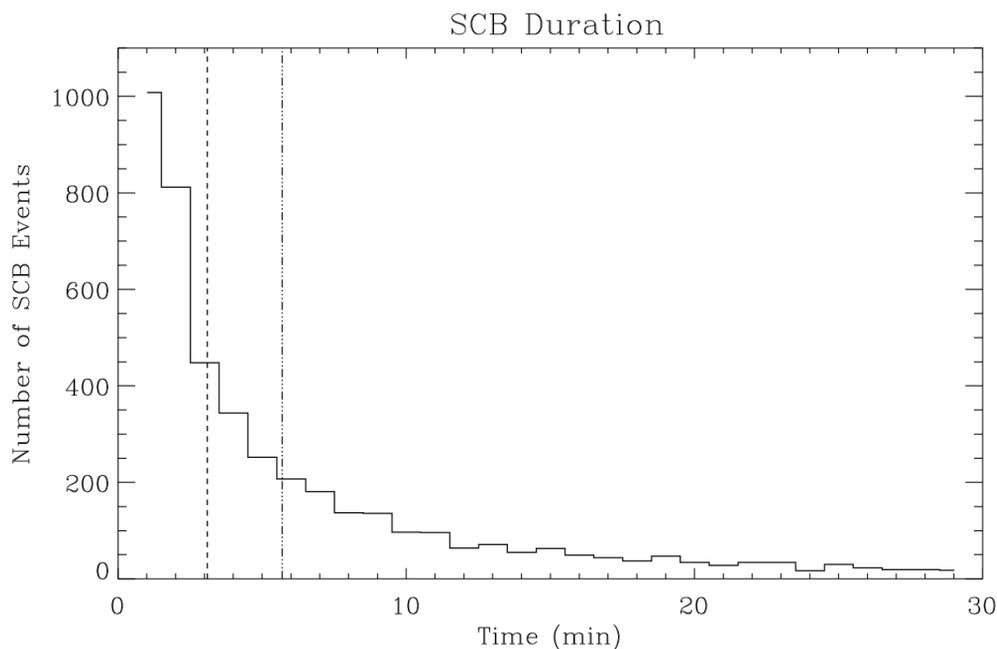
**Figure 1: A Two-Ribbon Flaring Event from 13 May 2005**

An animated time series of sequential images covering an erupting flare reveals several physical characteristics of evolving ribbons: the ribbons separate, brighten, and change their morphology. Adjacent to the eruption, SCBs can be observed brightening and dimming in the vicinity of the ribbons. Kirk et al. [4] describe in detail techniques and methods used to extract quantities of interest such as location, velocity, and intensity of flare ribbons and SCBs. The thresholding, image enhancement, and feature identification are tuned to the ISOON data. The detection and tracking algorithms are specialized for each feature of interest and requires physical knowledge (e.g. size, peak intensity, and longevity) of that feature being detected to isolate the substructure. Briefly, the detection algorithm first identifies candidate bright kernels in a set of images. In this

context, we define a kernel to be a locus of pixels that are associated with each other through increased intensity as compared with the immediately surrounding pixels. Each kernel has a local maximum, must be separated from another kernel by at least one pixel, and does not have any predetermined size or shape. Next, the algorithm links time-resolved kernels between frames into trajectories. A filter is applied to eliminate inconsistent or otherwise peculiar detections. Finally, characteristics of bright kernels are extracted by overlaying the trajectories over complementary datasets.

## 4 Results and Discussion

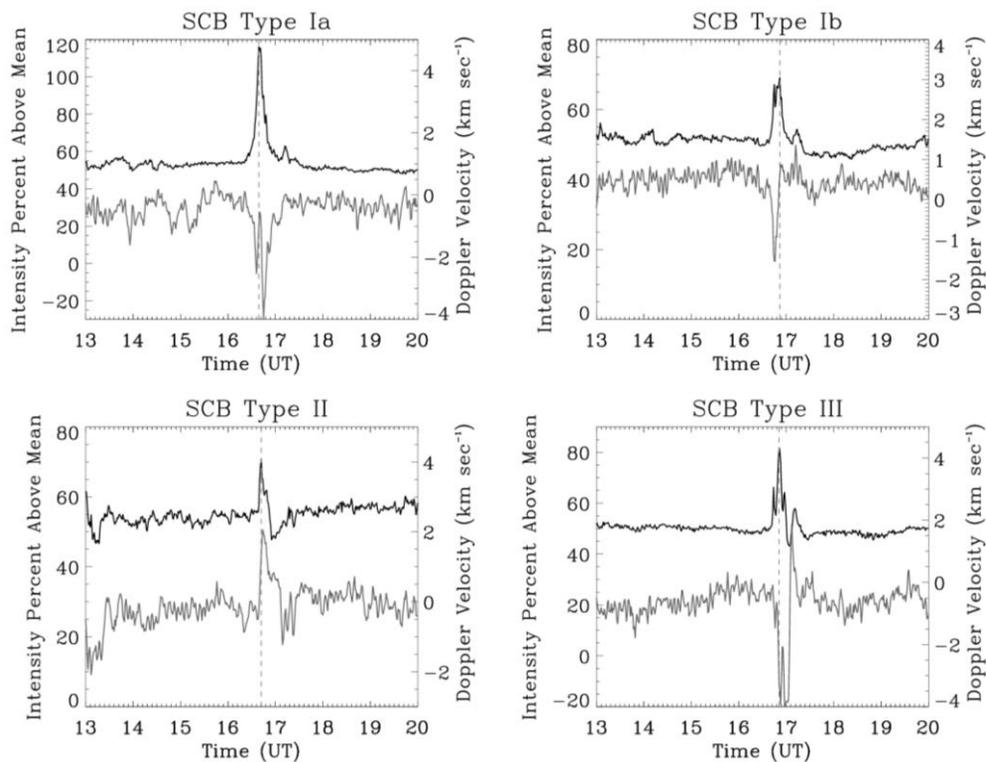
Figure 2 examines SCBs as a total population. The intensity brightenings have a median duration of 3.1 minutes (dashed line) and a mean duration is 5.7 minutes (dot-dashed line). The duration is characterized by the full-width half-maximum of the SCB intensity curve. A histogram of the distribution of the number of SCB events as a function of duration shows an exponential decline in the number of SCB events between 2 and 30 minutes. The duration of SCBs is uncorrelated with both distance from flare center and the peak intensity of the SCB.



**Figure 2: A Histogram of the Duration of All SCB Detections 3 Events Studied**

SCBs, although related to erupting flare ribbons, are distinctly different. Six SCBs are chosen from a 13 May 2005 event as an example of these ephemeral phenomena. The SCB intensity curve is significantly different from the flare kernels. SCB curves are impulsive; they have a sharp peak and then return to background intensity in the span of about 12 minutes. Nearly all of the SCBs peak in intensity before the peak of the flare.

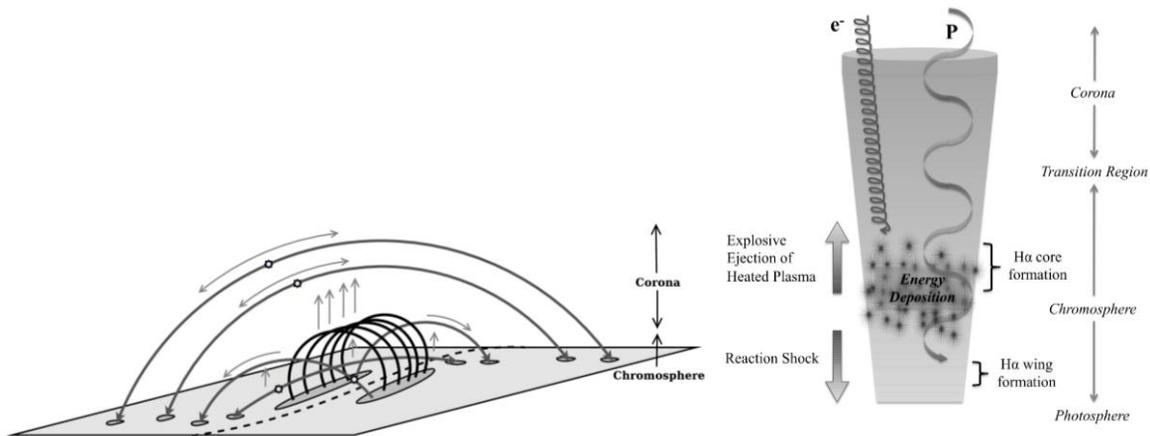
Examining Doppler velocity measurements from the SCB locations reveals three distinct types of SCBs as shown in Figure 3. A type Ia SCB has an impulsive intensity profile and an impulsive negative Doppler profile that occurs simultaneously or a few minutes after the peak brightening. In this study, a negative velocity is associated with motion away from the observer and into the Sun. A type Ib SCB has a similar intensity and Doppler profile as a type Ia but the timing of the impulsive negative velocity occurs several minutes before the peak intensity of the SCB. The type Ib SCB shown in Figure 3 has a negative velocity that peaks 10 minutes before the peak intensity and returns to a stationary state before the intensity has decayed. A type II SCB has a positive Doppler shift perturbation that often lasts longer than the emission in the intensity profile. The timing of both are nearly coincidental. A type III SCB demonstrates variable dynamics. It has a broad  $H\hat{I}\pm$  intensity line center with significant substructure. A type III SCB begins with a negative Doppler profile much like a type I. Before the negative velocity perturbation can decay back to continuum levels, there is a dramatic positive velocity shift within three minutes with an associated line center brightening. In all types of SCBs the typical magnitude of Doppler velocity perturbation is between  $2$  and  $5\text{ km s}^{-1}$  in either direction perpendicular to the solar surface. The vertical dashed line marks the peak intensity of the associated SCB. A negative Doppler velocity is away from the observer and into the Sun.



**Figure 3: Line Center Intensity and Doppler Velocity Measurements for Three Different Types of SCBs Observed in Two Flares**

## 5 Conclusions

Detailed conclusions of this work are found in [5,6]. Figure 4 is a proposed phenomenological model of the overlying physical topology. On the left, a dashed line marks the neutral line in this model. The central loops represent the emerging two ribbon flare arcade. The arches represent field lines connecting outside of the flare ribbons. The arrows on top of both the loops and arches show the direction trapped plasma flows as the flare begins to erupt and the stars suggest the location where the plasma is disrupted. Once perturbed, the trapped plasma streams down the loop lines and impacts the chromosphere causing the  $H\alpha$  intensity brightening. The different orientations of off-flare loops accounts for the different propagation speeds of SCBs observed. SCBs are hypothesized to be caused by electron beam heating confined by magnetic loop lines over-arching flare ribbons. These over-arching loops are analogous to the higher lying, unsheared tethers in the breakout model of CMEs. As the flare erupts, magnetic reconnection begins in a coronal x-point. The CME escapes into interplanetary space, the remaining loop arcade produces a two ribbon flare, and the tethers reconnect to a new equilibrium position. The tether reconnection accelerates trapped plasma which impacts the denser chromosphere causing observed brightening. This description implies the driver of SCBs is the eruption of a CME. A simple loop configuration without localized diffusion or anomalous resistance implies that the length of the loop directly proportional to the travel time of the electron beam.



**Figure 4: Illustrative Models That Arise from the Analysis of SCBs**

Examining single SCBs, the coincident Doppler recoil with the  $H\alpha$  intensity presents a contradiction. If an SCB is an example of compact chromospheric evaporation, then the only Doppler motion should be outward, the opposite of what is observed. Figure 4 presents a possible solution to this on the right hand side. Electrons and protons accelerated by magnetic reconnection further up in the corona come streaming down the flare loop. Since the mean free path of electrons is significantly less, the electrons deposit energy into the upper chromosphere. Unable to radiate the energy as heat, the chromosphere explosively responds by sending material back up the flux tube (chromospheric evaporation) and a reaction shock propagates towards the photosphere. This reaction shock explains the velocities observed in Type I SCBs.

Since the scattering length of electrons is significantly smaller than that of protons, the electron beam impacts the mid chromosphere and deposit energy into the surrounding plasma while the protons penetrate deeper. This deposited heat cannot dissipate effectively through conduction or radiation and thus expands upward into the flux tube. Since the Doppler measurements are made in the wings of the line, the location of the Doppler measurement is physically closer to the photosphere than the  $H\hat{I}\pm$  line center. Thus the observer sees the heating of the line center and coincidentally observes the recoil in the lower chromosphere.

In type II SCBs an up-flow is observed. This is an example of a classic chromospheric evaporation where the heated plasma in the bulk of the chromosphere is heated and ablated back up the flux tube. In contrast, the type III class of SCB present an interesting anomaly to both the other observed SCBs and the model proposed in Figure 4. Since there is an initial down-flow, the beginning state of type III SCBs are similar to type Is. As the recoil is propagated, a continual bombardment of excited plasma (both protons and electrons) impacts the lower chromosphere, causing ablation and changing the direction of flow.

Two conclusions can be made about the flares studied in this work: first, the asymmetrical motions of the flare ribbons imply the peak flare energy occurs in the low lying arcade, and second, flare related SCBs appear at distances on the order of 105 km and appear as sites of compact chromospheric evaporation. It should be possible to estimate the reconnection rates with the addition of photospheric magnetograms. Associating vector magnetograms with this technique and a careful consideration of the observed Doppler motions underneath the ribbons would provide a full 3D method for estimating the Lorentz force for subsections of a flare ribbon.

SCBs are a special case of chromospheric compact brightening that occur in conjunction with flares. The distinct nature of SCBs arises from their impulsive brightenings, unique Doppler velocity profiles, and origin in the impulsive phase of flare eruption. These facts combined demonstrate that SCBs have a non-localized area of influence and are indicative of the conditions of the entire flaring region. They can possibly be understood by a mechanism in which a destabilized overlying magnetic arcade accelerates electrons along magnetic tubes that impact a denser chromosphere to result in an SCB. This distinguishes SCBs from the flare with which they are associated.

All results of this project are detailed in the three refereed papers [4,5,6] published by graduate student Kirk, and presentations he has given at several professional meetings [2,7,8,9].

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