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BURSTS, BOMBS, AND EXPLOSIVE EVENTS: MAGNETIC RECONNECTION IN THE LOWER SOLAR ATMOSPHERE

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ABSTRACT

Write an abstract.

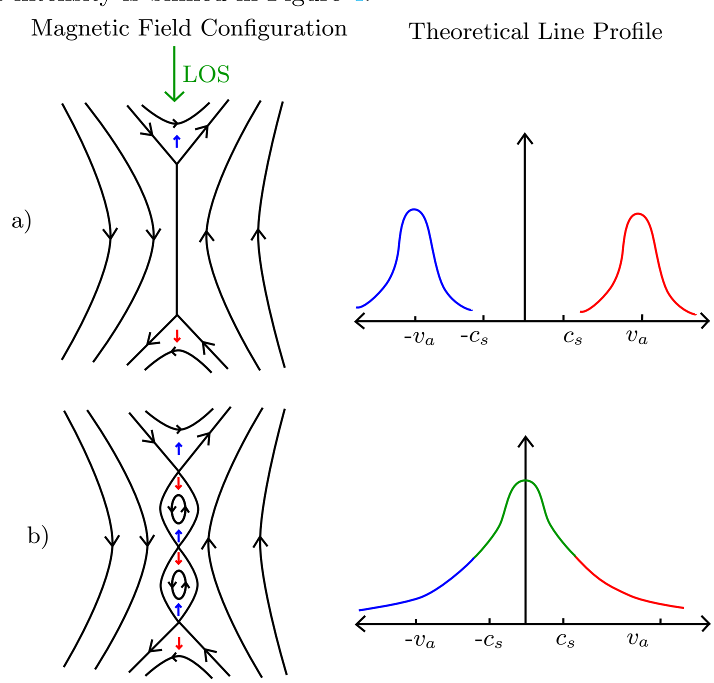
1. BACKGROUND

1.1. *Transient Brightenings in the Lower Solar Atmosphere*

From the photosphere to the upper reaches of the transition region the solar atmosphere changes three orders of magnitude in temperature over only a few thousand kilometers. This thin layer of the Sun, while often less grand in appearance than the corona, plays an important role in the energy transport required to heat the corona to mega-Kelvin temperatures. Like the flickering coals of a camp fire the photosphere, chromosphere, and transition region are littered with small, short lived, brightenings. Brightenings give us clues as to how often, where, and when energy produced in the solar interior is deposited beyond the photosphere.

These small brightenings are often accompanied by fast motion. Spectroscopic observations reveal many events, over a range of heights and temperatures, that have Doppler velocities exceeding the local thermal speed. In order for plasma velocities to exceed thermal speeds there must be a conversion of a non-thermal

Figure 1. Here we present a cartoon representing an ideal presentation of magnetic reconnection and corresponding spectral observation. Panel a shows Petscheck reconnection with bi-directional outflow jets at the Alfvén Speed, v_a. Plotted along side is a theoretical line profile, for the labeled *Line Of Sight* (LOS), showing two seperate peaks in intensity at $\pm v_a$. Panel b shows the developement of magnetic islands during the onset of the tearing mode instability. The addition of stationary emitting material will fill out line center and result in a broadened, mostly centered line profile. The blue, green, red coloring of the line profiles demonstrated how line intensity is binned in Figure 4.



energy source to kinetic energy. It is becoming widely accepted that this extra energy comes from the solar magnetic field. Through magnetic reconnection the Sun's magnetic field eliminates high energy discontinuities and converts that energy in to the heating and motion of local plasma. While repeated observations of non-thermal plasma motion within regions of complicated magnetic field has the solar physics community leaning toward magnetic reconnection as the cause of solar atmospheric heating the details are still the subject of much debate.

1.2. *Ellerman Bombs and Explosive Events*

Two commonly observed events in the Sun's lower atmosphere are Ellerman Bombs (EBs) and Explosive Events (EEs). EBs (Ellerman 1917) are commonly observed as intense brightenings in the wings of Hα λ6563 Å are characterized by small spatial scales (arcsecond or smaller), and short life times (a few minutes). Hα has a peak formation temperature of $\approx$ 10000 K placing EBs very low in the solar atmosphere near the photosphere. EBs are observed in regions of opposing magnetic polarity and, until recently (Nelson et al. 2017), exclusively within active regions. EBs are believed to be the result of magnetic reconnection as new flux emerges through the photosphere and reconnects with the preexisting photopsheric magnetic field. High resolution instruments such as the Crisp Imaging Spectropolarimeter (CHRISP; Scharmer et al. 2008) on the Swedish Solar Telescope (SST; Scharmer et al. 2003) and the Interface Region Imaging Spectrometer (IRIS; De Pontieu et al. 2014) have helped discover more details about EBs. They often originate between granules deep in the photosphere, have an upward extending flow or "jet", and demonstrate very fast variations (on second timescales) coupled with repeated eruptions (Watanabe et al. 2011; Vissers et al. 2013, 2015)

EEs were first analyzed by Brueckner & Bartoe (1983) using data from the High Resolution Telescope and Spectrograph (HRTS) sounding rocket. EEs are typically characterized by Doppler shifts on order 100 km s^{-1} and spatial scales of a few arcseconds (Dere et al. 1989; Dere 1994). Si IV λ1393Å rasters taken by the Solar Ultraviolet Measurement of Emitted Radiation (SUMER) sounding rocket revealed an EE with bi-directional jets near small magnetic bi-poles on the solar surface (Innes et al. 1997). This presentation was said to match the classic magneto-hydrodynamic (MHD) model of reconnection (Petschek 1964) quite well which is illustrated in Figure 1(a). Data from the first flight of the Multi-Order Solar EUV Spectrograph (MOSES; Fox et al. 2010) sounding rocket showed evidence of many explosive events in He II λ304Å. While a large number of events showed clear bi-directional jets with Doppler velocities of approximately $\pm$ 100 km s^{-1} (Rust 2017), one event showed fast jets, offset spatially, with a bright stationary core (Fox et al. 2010). Fox et al. (2010) identified a possible cause of the complicated spatial/spectral signature to be the Tearing Mode Instability (Furth et al. 1963) illustrated in Figure 1(b).

1.3. *IRIS Bombs and UV Bursts*

IRIS has been observing the transition region since late 2013. In this short period of time several discoveries have been made that have challenged our understanding of reconnection in the lower solar atmosphere. An early discovery by Peter et al. (2014) showed the presence of very cool, photospheric absorption lines in the wings of the Si IV λ1394Å line. Transient brightenings in Si IV with these types of absorption features have been labeled "IRIS Bombs" or "UV Bursts" and are thought to be caused by magnetic reconnection. The presence of the Ni II and Fe II absorption lines, with peak formation temperatures of approximately 15,000K, implies that IRIS bombs actually occur in the photosphere. Magnetic reconnection would heat plasma to at least 80,000K for Si IV formation, and emit through the cool photospheric plasma above it.

IRIS has also observed many events most similar to traditional EEs. While early work by Innes et al. (1997) showed EEs in Si IV to have bi-directional jets, later work by Innes et al. (2015) with IRIS Si IV data has shown EEs to have broad, almost triangular, line profiles with very bright cores and little to no sign of bi-directional flows. This was originally attributed to the Tearing Mode instability based on MHD simulations and synthetic line profiles. This theory has been corroborated recently by the observation of very small ($\approx$ 0."2) and very fast (less than a second) brightenings by SST that are co-spatial with Si IV UV Burst spectra (Rouppe van der Voort et al. 2017). These small brightenings are taken to be direct observation of Tearing Mode islands at transition region scales.

1.4. *Problem Statement*

Transient brightening in the lower solar atmosphere have many names and present themselves in a variety of ways. Names aside, these events have a lot in common. Consistently we see energy releases with on

Figure 2. Example explosive event map from our software package

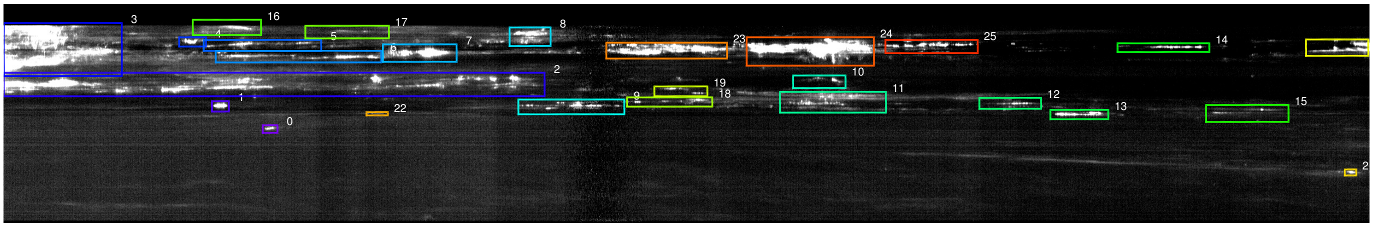
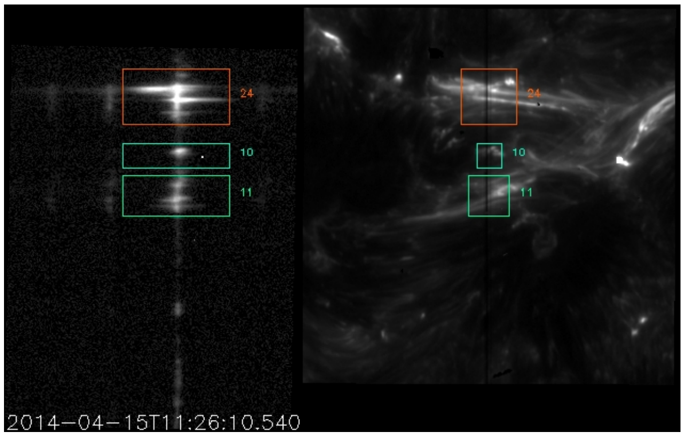


Figure 3. A single frame from an IRIS slit jaw context movie (right) side by side with corresponding slit spectra (left) shows event number 24 at a point in its evolution with a particularly sheared line profile.



order arcsecond spatial scales and second temporal scales. Spectrometers reveal that these small events have Doppler velocities exceeding local thermal speeds, and that they occur in a wide temperature band from 10^4-10^6 K. Due to their correlation with complex photospheric magnetic fields and super thermal velocities these events are all likely connected to magnetic reconnection, though not everyone is convinced (Judge 2015). Advances in instrumentation and modeling reveal the structure of the photosphere, chromosphere, and transition region to 3-D in nature. Throughout our study we will address the following science questions:

- Are EEs, UV Bursts, EBs, and IRIS Bombs truly different events, or are they all small reconnection events happening slightly different environments?
- If all of these events are associated with magnetic reconnection then what determines their presentation?
- What is the role of small reconnection events in transporting mass and energy to the corona?
- What can small reconnection events tell us about the role of the tearing mode instability in the onset of fast solar magnetic reconnection?

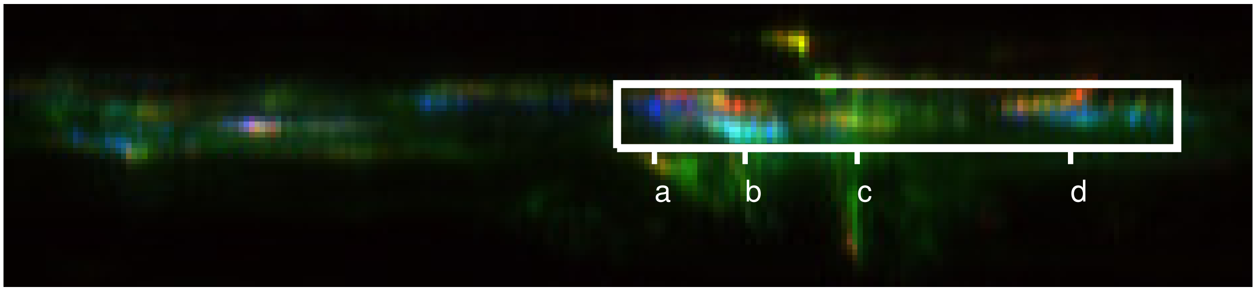
2. TECHNICAL APPROACH

The best tools currently available for studying magnetic reconnection in the lower solar atmosphere are high resolution spectrographs. We propose a multi-instrument statistical study of small transient brightenings. For this study we consider all brightenings, besides large flares, with significant super-thermal velocities to be Explosive Events (EEs) regardless of specific past definitions. Our study will begin with a detailed statistical study of Si IV spectra taken by IRIS and be supplemented with Ne VII and O V images taken by MOSES and the EUV Slitless Imaging Spectrograph (ESIS)

2.1. *Initial Survey and Event Selection*

We began our study by building a large database of EEs. To do this we selected a handful OBS IDs, IRIS observing programs, that best suited our needs. These OBS are all sit-and-stare observations with ≤ 4 second cadence, a medium or larger linelist, have limited spectral binning, and they must include the Si IV slit jaw data at least.

Figure 4. Color map of event number 24. This RGB image is generated by binning line profile intensity around a typical sound speed, in this case $v = 60$ km s^{-1}. Blue is the total intensity $\leq -v$, red is the total line intensity $\geq v$, and Green is the total intensity of the line core between $\pm v$. An example of this binning is illustrated in Figure 1. A transition from a separated blue/red intensity to a broader green profile is similar to a progression proposed in Figure 1.



We opt to use sit-and-stare data, as opposed to slit rasters, for increased temporal resolution. While it is easier to capture EEs using a rastered slit we have found that EEs evolve on a timescale much faster than the time it takes to complete even a small raster. Therefore, the best way to capture EE dynamics is to sit and stare.

With EEs evolving on second time scales we must make a trade between image cadence and signal to noise ratio. Over the last 4 years the FUV sensitivity of IRIS has diminished significantly. An exposure length that was long enough in 2013 is not long enough now. Fortunately for us EEs tend to be bright, allowing for good data with a sub four second exposure even with decreased sensitivity.

IRIS is an extremely flexible instrument that is limited in its data production by downlink telemetry bandwidth. Two methods of reducing memory usage are truncating data in the spectral dimension and binning data at the CCD level. We choose to use a medium line list or larger because it is the smallest line list that includes both Si IV spectral lines, λ1394 Å and λ1403 Å, which are required for optical depth diagnostics. We also allow more binning in spatial dimension, along the slit, than we do in the spectral dimension. If we hope to resolve narrow photospheric absorption lines, like Fe II and Ni II that are only a pixel or two wide, we need to take advantage of IRIS' high spectral resolution. We often bin spectra along the slit during analysis and therefore require less spatial resolution.

Since the bulk of our analysis centers on Si IV spectra we require all OBS for this study to have at least the Si IV λ1400 Å slit jaw images for context. Slit jaw movies show what is going on around the slit and are very useful for identifying and sorting different event spatial structure. An example of a slit jaw image is shown in Figure 3

This criteria gave us 23 OBS from April 2014 to May 2017. With more data coming down from IRIS everyday we will be able to expand this data set. As we approach solar minima we will add more observations of quiet sun targets to look for any associated trends. From these 23 OBS we have identified 581 events. To do this we used an EE software package developed at Montana State University which provides a simple GUI for event selection as well as worked with an REU student during the summer of 2017 (Bartz 2018). An example of our software in action can be seen in Figure 2. EE maps are made by integrating all material with a Doppler speed ≥ 60 km s^{-1} and making an image with slit position on the vertical axis and time on the horizontal. Then clumps of intensity in the image can be boxed via a click and drag interface. Each box represents an event. Our initial survey has shown our data set to cover a large portion of the solar disk, covering mostly active latitudes. Most events last 20 min or less and cover less than 10" of slit.

2.2. *Spectral Diagnostic IRIS*

Si IV has a peak formation temperature of $\approx 80,000$K placing it at the base of the transition region. IRIS has revealed this line to be both optically thin during small flaring events and show a variety of optical depth effects (Peter et al. 2014; Yan et al. 2015). Complex Si IV line profiles are being used to draw new conclusions about the location EEs, the type of magnetic reconnection causing them, and the fundamental structure of the lower solar atmosphere. We wish to study Si IV line profiles to determine which behaviors are statistically significant and which are anomalous events that contribute less to our overall understanding of EEs.

We will start by sorting EEs into optically thin and optically thick events. To do this we will monitor the line ratio of both Si IV lines throughout the course of each event. Si IV λ1394 Å and λ1403 Å maintain a 2:1 ratio during optically thin conditions (Mathioudakis et al. 1999). Significant deviations from this line ratio indicate an event has significant absorption or is optically thick. Optically thick line profiles will need to be handled differently when determining Doppler shifts. Absorption features would need to be masked off when analyzing line profiles. We are also interested in the distribution of line ratios across the EE database in order to address the question of whether events with or without optical depth effects are unique, or the product of how we observe them.

The next step is to identify typical velocity distributions during EEs. Observations of EEs in the past have shown them to be both bi-modal (Innes et al. 1997; Rust 2017) and have more continuous velocity distributions with 3-D structure (Fox et al. 2010; Innes et al. 2015; Rouppe van der Voort et al. 2017). We will determine what portion of events deviate from the bi-modal Petschek reconnection picture of EEs by using Doppler maps like in Figure 4. By binning spectral intensity by Doppler shift we can quickly see events that have directional flows (blue or red) and those that are more complicated and have significant line core emission (green). Identifying blue/red to green transitions over time may help us understand the onset of the tearing mode instability and the transition to fast reconnection. A more complicated method of analyzing velocity distributions would be to deconvolve thermal gaussians from the line profile. This would allow us to distinguish between highly structured velocity field from reconnection outflows and turbulent flows.

The IRIS slit jaw movies give spatial context for each event. Spatial context allows for further event classification. For example Figure 3 shows a frame from the Si IV slit jaw movie associated with event 24 in Figure 2 next to its corresponding spectra. From this frame we can see that event 24 is associated with a visible loop. We can then correlate observed Doppler velocities with apparent motion along the loop. An alternative would be a compact brightening with no obvious spatial structure, an observation off limb, a sun spot penumbra, etc. This context is vital for interpreting spectral information as an indication of spatial structure.

Say something about future work with C II or HMI? Or is the scope getting too far out? Mention despiking the data?

2.3. *ESIS and MOSES-3*

The ESIS/MOSES-3 sounding rocket launch is currently scheduled for Fall of 2018. ESIS and MOSES both use convex diffraction gratings to focus light from different spectral orders onto separate CCDs. Each image represents a different projection through a 3-D cube with two spatial and one spectral dimension. MOSES data from the previous two launches has already been inverted successfully via a few different methods (Fox et al. 2010; Courrier & Kankelborg 2015; Smart et al. 2016, 2017; Rust 2017) demonstrating its ability to provide simultaneous spectral and spatial measurements over it's entire field of view. ESIS will improve on MOSES' design by adding additional CCDs, four cameras to start with the possibility of six for future launches. It also includes a field stop which will limit spectral contamination from objects beyond its field of view (Parker & Kankelborg 2016).

ESIS images primarily in O V λ630 Å with a portion of the detector capturing He I λ584 Å and MOSES-3 images in Ne VII λ465 Å. These lines have peak formation temperatures of 224,000 K, 10,000K, and 500,000 K respectively. Comparing EEs in hotter transition region lines with those in Si IV will help place events at a height in the atmosphere and map the flow of mass and energy from photosphere to corona. Not to mention if we are lucky enough to catch an event in both O V and He I with ESIS we will see that EEs have a wide variation in temperature across a single event. Comparing Doppler shifts between cooler and hotter lines will also how material and energy are transfered from photosphere through the transition region to the corona.

A slitless spectrograph has many advantages over traditional spectrographs when viewing explosive events. A large field of view eliminates the need for slit rastering to find velocity fields. Since Doppler information is co-temporal across the field of view there is no issue of the velocity field evolving faster than one can raster. Coordination with IRIS and the ESIS/MOSES-3 sounding rocket is relatively simple. MOSES and ESIS have significantly larger fields of view than IRIS and since they capture Doppler shifts over the entire field of view there is no risk of slit misalignment. IRIS slit jaw images allow for simple co-alignment with ESIS/MOSES-3 images.

We believe that slitless spectrograph will provide unprecedented insight into reconnection events in the lower solar atmosphere. With access to Doppler velocities across an entire event with every exposure we no longer have to wonder what is happening in an object, or a portion of an object, that is off slit. We can also make velocity maps co-temporally in multiple lines at multiple temperatures, getting us one step closer to mapping energy flow through the lower solar atmosphere.

3. SCIENTIFIC IMPACT

Preforming a detailed statistical study of small energy releases in the lower solar atmosphere has a lot to offer the broader scientific community. Magnetic reconnection is a physical process of universal significance. Fusion reactors, the Earth's magnetotail, coronal heating, etc. are all impacted by magnetic reconnection. EEs are great way to study reconnection for few reasons. They are more frequent than large flares, providing better statistics. EEs tend to be compact allowing for a slit spectrograph to capture Doppler velocities over a larger portion of the event. They also occur in a narrow portion of the Sun's atmosphere where there is less "stuff" to look through. We believe that magnetic reconnection contributes largely to the variability of the Sun and , in turn, the space weather environment. A more thorough understanding reconnection with help minimize it's impact on humanity by improving our predictive capabilities.

While many publications exist on IRIS observations of EEs, most of them focus on a few tens of events or less. Large statistical studies are going to become more and more common in our field. In a time where Heliophysics satellites are taking gigabytes of data a day we need to be focused on analysis methods that are catered to large data sets. With no shortage of observations available we can use statistically significant sample sizes prior to drawing broad conclusions. Developing the machinery to analyze EE spectra in a semi-automated will make expanding our statistics simple throughout the remainder of the IRIS mission. Questions that arise during the study will also motivate future IRIS observing plans and help increase its scientific productivity.

ESIS/MOSES-3 represent the next generation of solar spectrometers. Work on these sounding rockets gets us closer to the ultimate ideal in spectroscopy, full disk co-temporal spectral/spatial images. While we are still a ways off, advances in slitless spectroscopy will slowly dissolve our reliance on the medieval arrow slit or slit spectroscopy and give us back our field of view.

4. TIMELINE

Get a degree, and maybe some extra money in the meantime.

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