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Temporal and Spatial Relationships Between Ultraviolet and
Hard X-ray Emission in Solar Flares

by

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ABSTRACT

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The temporal and spatial relationships between hard X-ray and UV emission in solar flares provide stringent restrictions on the physical processes responsible for solar flare emission. In this thesis, we present results from a detailed analysis of temporal profiles and spatially resolved hard X-ray images from RHESSI alongside high cadence observations of the UV continuum from TRACE for two solar flares: A C6.5 flare from 16 July 2002 6:38-06:43 UT and an M8.5 flare from 17 July 2002 07:00-07:05 UT. For both flares we find a significant temporal correlation between the UV and hard X-ray emission over the duration of both events. In the spatial analysis for the 16 July 2002 event, we note a significant spatial separation between the correlated UV sources and their hard X-ray counterparts leading to a complex flare topology invoking loop-loop interactions. We suggest a three-dimensional reconnection scenario in an attempt to address the spatial discrepancy in the hard X-ray and UV correlated emission.

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Chapter 1

Introduction

Although, the Sun is one of the most frequently observed objects in astronomy, it is still not sufficiently well understood to explain the widely varied impulsive behavior it exhibits. Among the notable embodiments of this impulsive behavior, solar flares and coronal mass ejections (CMEs) provide unique insight into magnetically-driven energetic phenomena occurring in an astrophysical object. These transients are crucial to the physical understanding of the Sun-Earth system because energy released can directly affect the Earth through the creation of geomagnetic storms and other space weather events. High energy particles associated with these storms can adversely affect human and material resources in space as well as ground-based electrical systems. Though CMEs are primarily responsible for most geo-effective events (Weiss et al. 1996), energy release in solar flares, believed to be driven by magnetic reconnection, provides insight into the physical processes that govern transient activity in the solar atmosphere.

Solar flares are events in which significant amounts of energy are released from the solar magnetic field resulting in a variety of responses within the solar atmosphere. In general, these events can be described by three phases: a pre-flare phase, an early build up to flare frequently exhibiting sporadic low intensity activity; an initial

impulsive phase, often seen as a period of short-duration intense hard X-ray bursts depicting the immediate atmospheric response to the primary energy release; and a gradual phase, showing the steady eventual decay of the energy over longer timescale (often as long as several hours). The mechanisms responsible for the impulsive phase response are not well understood. However, multi-wavelength observations are crucial to providing stringent requirements on the physical processes driving the impulsive response and thus the energy release process itself. We focus on the relationships between simultaneous UV and hard X-ray emissions (defined in our case as emission from 25-200 keV to minimize the contributions from thermal electrons) during the impulsive phase. Both of these emissions are believed to be the direct result of energy injection into the chromosphere from the initial release and as such provide diagnostics of the energy release process.

Studies of UV and Hard X-ray (HXR) responses during the impulsive phase of flares began in the late 1960's when satellite observations became available. These results were based on hard X-ray observations by the Orbiting Geophysical Observatories (OGO) and nearly simultaneous ground-based measurements of sudden frequency deviations (SFD) in the ionosphere in the extreme ultraviolet (EUV) bandpass. Such studies gained prominence in the 1980's, during the Solar Maximum Mission (SMM), which focused on the temporal relationship between the ultraviolet and the hard X-ray emission. Chung-Chieh Cheng and a number of collaborators authored many

observational studies of the timing of UV and hard X-ray emissions (e.g. Cheng et al., 1981;1987;1988). Their studies focused on correlations in the time profiles of hard X-ray emission measured with the Hard X-Ray Burst Spectrometer (HXRBS) instrument with imaged UV continuum observed with the Ultraviolet Spectrometer and Polarimeter (UVSP), both on SMM. These early progressions in the advancement of UV-hard X-ray observations and theories provide the groundwork for the research reported in this thesis.

1.1 Early Studies through the Solar Maximum Mission

The initial studies of hard X-ray timing correlations with that of broadband EUV emission stemmed from observations from the OGO satellites and ground-based measurements of sudden frequency deviations in the ionosphere for frequencies in the EUV range (10-1030 Å) (Kane and Donnelly 1971; Donnelly and Kane 1978; and Kane, Frost, and Donnelly 1979). In the first paper of this series, several flare events were examined during the period 1967 to 1969 using ionization chamber data from OGO-1 and OGO-3 and NaI scintillation chamber data from OGO-5. A majority of the data presented were measurements from the scintillation chamber on OGO-5. The chamber collected hard X-ray data in eight channels (9.6-19.2, 19.2-32, 32-48, 48-64, 64-80, 80-104, 104-128, >128keV), and had a temporal resolution of 2.3 seconds. The X-rays profiles were compared with broadband EUV profiles obtained from the SFD analysis which had a time resolution of approximately one second.

The results of three such flare events are shown in Figure 1.1. Each event shows a very similar rise in both the EUV and hard X-ray channels (pictured are the 9.6-19.2 and 19.2-32 keV channels). The analysis is limited to this part of the flares partially due to a desire to focus of the impulsive phase of the flare, but also due to unreliability in SFD data during the decay phase.

Figure 1.1 Figure 2 from Kane and Donnelly, 1971 showing comparisons of the impulsive rise of three flares in broadband EUV, 9.6-19.2 keV X-rays, and 19.2-32 keV X-rays.

Building on these observational results, Kane, Frost, and Donnelly put forth a model of the partial precipitation of energetic electrons to reproduce the UV-HXR relationship (1979). In this model, they theorize that hard X-ray sources in the chromosphere are produced through thick-target bremsstrahlung while the EUV emission is the result of chromospheric heating resulting from the transfer of kinetic energy

from the precipitated electrons from the injected non-thermal electron beam to the high-density chromosphere through predominantly Coulomb collisions. This partial precipitation model invokes three density regions and a strongly converging magnetic field to produce the observed X-ray footpoint and EUV emission. The Kane et al. model describes the flare as a single magnetic loop with the magnetic field converging with atmospheric depth. The non-thermal electrons are injected in the low-density corona and travel along the magnetic field lines into one of two higher density regions. The electron mirror in the higher density regions dependent on the pitch angle of the electrons. The electrons which reach the high-density region in the chromosphere do so through either direct precipitation with pitch angles that permit passage through the magnetic trap, or as part of a later developing population which is the result of scattering within the trap. Those electrons reaching the medium density chromospheric region produce hard X-rays through bremsstrahlung emission while those precipitating to the high-density region produce UV and EUV emission through bulk chromospheric heating. Coronal X-ray sources in this model are produced by electrons trapped in the medium density region through thin-target bremsstrahlung emission. Refinement of trap-plus-precipitation model continued throughout the 1980's and 1990's (Alexander, 1990; Alexander and Metcalf, 1997; MacKinnon, 1988; McClements, 1990). These models were able to reproduce the observed HXR fluxes in the flare footpoints while also reproducing observed coronal X-ray signatures, from

the trapped particles.

With the Solar Maximum mission of the 1980's, the question of UV-HXR relationships continued to be a prominent focus in flare studies. One of the more prominent studies during this timeframe was that of Cheng et al. (1988). Like the Kane et al. studies, the focus was predominantly temporal as the instruments on board SMM did not allow for the imaging of hard X-ray sources above ~ 30 keV. The HXR data in this study came from the Hard X-Ray Burst Spectrometer (HXRBS) instrument. The Hard X-ray Imaging Spectrometer (HXIS) imaged X-rays for energies less than 30 keV where the spectrum has a significant thermal component making the non-thermal, flare-accelerated electron signatures difficult to isolate. The UV images were taken by the SMM/UVSP with a field of view of 30x30 arcseconds square. The UV Data concentrated on the OV line at 1371 Å and a wide-band UV continuum measurement around 1388 Å (Cheng et al, 1988). For each event covered, a cross-correlation analysis was performed on the time signatures for the hard X-rays in comparison with both the UV continuum and the OV line. This analysis permitted a determination of any lags between the various emissions

Sample data from the Cheng et al. studies (Figure 1.2) show a strong correlation in the impulsive bursts at all three wavelengths. Within the time resolution of this study (0.128 seconds), a 0.3 to 0.7 time lag was reported between the UV and hard X-ray peaks with the hard X-rays leading the UV emission. It was also reported that

Figure 1.2 Example lightcurves of a May 24, 1985 flare from Cheng et al (1998). The labeled bursts are corresponding pulses in all three wavelengths.

the correlation coefficient varies with the progression of the flare through a series of burst with the strongest correlation being coincident with the peak burst of the hard X-rays. Cheng et al. (1988) also demonstrated the existence of spatially localized UV and HXR emission. They reported that the majority of the sources observed in the UV were approximately 4 arcseconds in width which corresponds to the UVSP instrument resolution (images focused on the Si IV lines). The motions of these sources provide evidence for the commonly held belief that these UV kernels were footpoints at the base of the flaring coronal loops. These UV kernels can be viewed

as individual sources which correspond to specific brightening peaks within the UV lightcurve (Cheng et al., 1981; 1987).

Addressing the physical processes behind these results, Cheng et al. (1988) compared their UV line and continuum emission observations with the predictions of a number of models for hard X-ray and UV production. The results of these comparisons will be addressed in section 1.3.

1.2 Studies with YOHKOH and TRACE

The advancement of solar flare research in the 1990's was achieved in part through the launch of the YOHKOH and TRACE missions (SOHO was predominately a non-flare mission although it has made major contributions to CME research and flare-related phenomena in collaboration with other missions). These spacecraft provided increased spatial and spectral resolution, at their respective wavelengths. TRACE provides the capability to image in a number of UV wavelengths with a spatial resolution of approximately 1 arcsecond while imaging every 1 to 2 seconds at its highest cadence. The YOHKOH spacecraft and in particular the Hard X-ray Telescope (HXT) instrument allowed for hard X-ray imaging in 4 X-ray channels (Lo: 13-23 keV, M1: 23-33 keV, M2: 33-53 keV, and Hi: 53-93 keV). Using data collected from these new instruments Warren and Warshall (2001) revisited the relationships between UV emission and hard X-ray emission in flares. Their study consisted of nine flares exhibiting coincident flare emission in the UV continuum quadrant of TRACE (peaking

at $1600\text{\AA}$) and in YOHKOH/HXT. The earliest flares in the study relied on hard X-ray observations made by the Burst and Transient Source Experiment, (BATSE) a hard X-ray instrument on board the Compton Gamma Ray Observatory with high sensitivity above 25 keV which had no imaging capability. The TRACE data was taken at a cadence of 2-3 seconds. In the example shown in Figure 1.3, Warren and Warshall (2001) compare the lightcurves of six identified UV sources from an M1.1 flare occurring on 17 March 2000 with the composite hard X-ray lightcurve generated from BATSE data in the 25-50 and 50-100 keV channels.

Figure 1.3 Comparative lightcurves of a March 17, 2000 flare (TRACE curve in foreground). Analysis of these lightcurves indicates a correlation between hard X-ray sources and UV sources which showed no preflare emission. (Warren and Warshall, 2001)

Three sources experienced intense brightening prior to the hard X-ray onset (see Figure 1.3). Warren and Warshall performed a regression analysis on the sources shown and found a strong correlation between UV sources with minimal preflare activity (sources D and E) while sources which were active prior to hard X-ray onset are uncorrelated or in some cases anticorrelated to the hard X-ray emission during the flare (Warren and Warshall, 2001). Of the nine events studied, five of them were observed with HXT allowing for the hard X-ray sources to be spatially resolved to within approximately 8 arcseconds. Two flares observed under these conditions were singled out as examples of the spatial separation between the hard X-ray emission sources and the UV brightenings. This separation suggests a more complex configuration than the single loop often invoked in models such as the trap-plus-precipitation model. Figure 1.4 contains two UV images from TRACE with overlaid contours of the HXT image reconstructions. The first image in Figure 1.4 shows the initial UV ribbon development prior to the onset of hard X-ray production. The second image is an observation from near the onset of initial hard X-ray burst. While the UV emission exhibited long flare ribbon structures, the hard X-ray bursts from this event appeared localized at one end of the of the central ribbon.

1.3 Implications for Energization Models

Due to the complexity of the energization process of solar flares, a variety of models have attempted to reproduce the observed relationships between the emissions at

Figure 1.4 TRACE UV images from the 22 January 2000 flare in the study. The left image shows the development of a UV ribbon structure prior to the onset of hard X-ray emission. The right image is taken during the initial hard X-ray burst. The hard X-ray emissions are clearly more localized than the UV emission (Warren and Warshall, 2001)

multiple wavelengths. As instrumentation has improved, observations of spatial and temporal profiles of the various emissions have been refined sufficiently to determine the lag times between and the spatial separation of emissions at various wavelengths placing strict limitations on the mechanism for energy deposition in the chromosphere. Observations of UV and hard X-ray emission being temporally correlated to within 1 second (Cheng et al. 1988, Woodgate et al. 1983) has ruled out thermal conduction models, such as those put forth by Brown, Melrose, and Spicer (1979) and Smith and Lilliequist (1979). In these models, the hard X-ray production takes place in the corona near the tops of large loop structures while the UV production occurs in the chromosphere at the base of such structures. Energy transport here relies upon

thermal conduction fronts which travel at or near the local sound speed (Brown, Melrose and Spicer, 1979) for the energy to reach the chromosphere and thus requires a time lag of 6-20 seconds for the UV emission relative to the hard X-rays (Woodgate et al 1983).

Cheng et al. (1988) also compared their observations to a number of other models including non-thermal electron beam models, hole boring models, in which an initial beam creates a high-temperature and low-density channel in which subsequent beam electrons precipitate (Cheng et al, 1988), and Alfvén wave heating models (Emslie and Sturrock, 1982). All of the models tested were unable to sufficiently reproduce observations given the timing, density, and spectral constraints. The difficulties of the models include the ability to generate enough energy at the needed chromospheric depths to produce the UV continuum emission and the ability to reproduce the observed temporal correlations.

In addition, the results of Warren and Warshall (2001) raise critical questions with regard to the spatial structure and topology of the flaring regions. The implication of the observed uncorrelated or anticorrelated preflare emission is that the flare consists of a more complicated topology than a single loop structure. Observations presented in this thesis utilize the improved spatial resolution provided by the Ramaty High Energy Solar Spectroscopic Imager (RHESSI) to investigate the spatial component of the UV/HXR relationship with higher fidelity than previously considered. The

combination of RHESSI and TRACE provides an unprecedented ability to observe small scale structure within both the UV and the hard X-ray sources and observe any notable spatial separations between the emitting regions. The time resolution improvements of RHESSI present an opportunity to refine the timing relationships reported by Warren and Warshall (2001) with improved accuracy to verify and build upon the correlation work reported previously.

1.4 Project Overview

Our present work advances the studies discussed in the preceding sections by incorporating the improved spatial and temporal resolution of RHESSI in conjunction with high resolution, high cadence observations by TRACE. RHESSI allows us to examine the spatial structure of the hard X-ray emission with resolution of 2 arcseconds. This improved resolution permits the observation of smaller scale hard X-ray sources not resolved with previous instruments.

The present study explores the issue of the temporal and spatial relationships between UV and hard X-ray emission in three main respects:

- The analysis of spatially-integrated UV and hard X-ray time signatures, and comparisons with the findings of the prior studies to verify the correlations suggested by their results.
- Comparison of individual UV sources with the overall HXR time evolution to

confirm the visual identification from TRACE images of active UV sources both during the individual hard X-ray bursts and during periods of preflare activity exploring the existence of correlations of preflare sources with the hard X-ray bursts.

- Warren and Warshall (2001) found that the preflare brightenings were either uncorrelated or anti-correlated with the hard X-rays. This study attempts to verify these findings with the improved instrumentation of RHESSI and TRACE. During the preflare initial brightenings TRACE has a poor time resolution of approximately 4 seconds. This cadence is sufficiently high to observe structure within the preflare time profile.
- Comparison of spatial associations between the imaged hard X-ray sources with the position of the UV sources are conducted for each major burst within the hard X-ray lightcurve.

From this spatial data we investigate the spatial separation of the UV and hard X-rays sources. We apply this information and the location of cotemporal UV brightenings to infer possible topologies for each of our flares.

We describe the instrumentation and methods used in the analysis of the UV and hard X-ray data in Chapter 2. Chapter 3 will present the results of example events in our study addressing both the temporal correlation as well as the spatial development

of the flaring regions. Chapter 4 will apply our findings to the question of magnetic structure differences and their effects on the flaring region. This will allow us to address potential topologies for our flare events based on our timing and separation results. We will conclude with a summary of our findings and suggestions for future extension of this work in Chapter 5.

Chapter 2

Instrumentation and Methodology

The analysis of hard X-ray and UV emission from solar flares presented in this thesis incorporates a number of diverse datasets from a variety of instruments. This includes UV continuum images from TRACE, high time resolution light curves and hard X-ray image reconstructions from RHESSI, and magnetogram and white light information from SOHO/MDI. In this section, crucial information about each of these spacecraft and datasets is provided while the specific aspects of the methods used are detailed.

2.1 Instrumentation

2.1.1 TRACE

The Transition Region and Coronal Explorer (TRACE) is a multi-wavelength high resolution ultraviolet and extreme ultraviolet imaging telescope. TRACE employs direct imaging through normal incidence on a 1024x1024 CCD array to image plasmas from 6000K to approximately 2MK. The images produced cover a maximum field of view of 512"x512" with each pixel being 0.5" on a side. The limited field of view presents instrument pointing difficulties for TRACE due to the lack of solar limb observation capabilities. One aspect of the instrument pointing which cannot be addressed through the TRACE data itself is the flexing of the metering tube

which holds together the aperture and CCD camera components of the instruments. The effects of this flexing are the primary reason for the co-alignment process with SOHO/MDI data (see Section 2.3) as uncorrected, these flexes can change the pointing of TRACE by 5-10 arcseconds.

The 30cm aperture of the TRACE telescope is divided into 4 quadrants, 3 for EUV imaging and 1 for imaging in the ultraviolet and visible light. A more detailed description of the TRACE imaging capability is discussed by Handy et al. (1998). For the purposes of this study, our focus is the UV imaging quadrant, and specifically the 1600Å UV and white light observations. We use data collected under the Flare-watch1600 observing program implemented by Harry Warren (See Section 2.2.2). We focus on the 1600Å observations because the narrowband filter used permits the imaging of the UV continuum with a FWHM of 245Å. Images taken at these wavelengths show emissions from plasma in the chromosphere through the transition region and low corona. The response function of this continuum filter in terms of percent transmission is shown in Figure 2.1. A manageable complication for this study is that the field of view of the 1600Å data varies depending on the count rate prior to shifting into flare mode, TRACE targets a 384"x384" field of view with 0.5" pixels. The small pixel size allows TRACE to resolve structures to within 1". The resolution in flare mode is also 1"; however, the field of view is reduced to 256"x256" to allow for a faster cadence. A key point of this program is the time resolution it provides.

Figure 2.1 Instrumental profiles of transmission efficiency versus wavelength for the TRACE 1600Å 1216Å and white light (Fused Silica) observations.

During flare mode operations, TRACE takes a UV continuum image approximately every two seconds. During the preflare stage the time resolution is approximately 4 seconds. This reduction is due to the larger field of view used in preflare imaging. In comparison, typical TRACE observing programs image the UV continuum at a one minute cadence at best if the wavelength is imaged at all.

In addition to the 1600Å images, our study also requires TRACE white light observations. These observations are taken through the UV quadrant of the TRACE instrument using a broadband fused silica filter, the response function of which is also shown in Figure 2.1. White light images are taken sporadically during TRACE flare observations, and serve the purpose in this study of providing a direct comparison with the SOHO/MDI white light full disk images. This comparison is required to correct inherent errors in the pointing information reported by TRACE. The co-

alignment procedure will be detailed in Section 2.3. Together, the white light and UV continuum images produced by TRACE provide insight into the progression of the well-resolved UV sources both before and during the hard X-ray impulsive flare.

2.1.2 RHESSI

The hard X-ray information used in this study is taken from observations by the Reuven Ramaty High Energy Solar Spectroscopic Imager (RHESSI). RHESSI is an X-ray and gamma ray imaging telescope with a spectral range from 3keV to 20MeV with a spectral resolution of $\sim 1\text{keV}$. RHESSI is a rotating modulation collimator telescope consisting of nine germanium detectors and nine rotating grids providing temporal resolution of tens of milliseconds at all energies. Spatially, the resolution varies depending how many and which of the nine grids are active (Lin et al 2002). Of key interest to this study is the RHESSI instrument characteristics for energies up to 100keV. Within this energy range the spatial resolution is approximately 2 arcseconds when the finest resolution grid is active.

RHESSI produces lightcurves from the measured number of photons collected for a given energy in a given time interval. The smallest time interval available is 0.1 seconds; however for most of our study these lightcurves have been binned to two second averages to match more closely the timing of the TRACE observations. The original RHESSI lightcurve shows 0.1 second temporal resolution, illustrating the small-scale variability in the X-ray signals. Binning the data to match the TRACE

resolution allows us to compare the UV and hard X-ray emission during large scale impulsive bursts.

Images are produced by Fourier transformation of the received modulation patterns (see Aschwanden et al. 2004 for details). The spacecraft completes a rotation every four seconds, yielding a modulation pattern in the signal which varies depending on the size and location of the source. In our study the RHESSI images are created with a 128"x128" field of view centered on the flare using pixels that are 2" on a side. Although a number of image reconstruction techniques are available (Aschwanden et al. 2004), we choose to work with the Pixon reconstruction method (Metcalf et al. 1996) due to the improved photometry that it provides. Taken as a complete package the RHESSI lightcurves and images provide the most temporally and spatially resolved hard X-ray data available.

2.1.3 Michelson Doppler Interferometer (MDI)

The Michelson Doppler Interferometer (MDI) is an instrument aboard the Solar and Heliospheric Observatory (SOHO) designed to obtain magnetograms and white light images for the entire solar disk. The MDI white light images provide a full-disk white light image at less resolution than the TRACE images but that clearly show similar features to those in the TRACE field of view. These similar structures provide selection points for image co-alignment and correction of TRACE metering tube pointing errors. Our second use of MDI is to use the full-disk magnetograms to deter-

mine the magnetic configuration and evolution within the active region responsible for the flare. The magnetic field changes provide insight into the potential magnetic topologies of the flaring region.

2.2 Key Aspects of Our Analysis

Involving multiple instruments and datasets presents a number of challenges with regard to the analysis performed. The challenges in the present analysis include defining the limiting criteria placed on event selection, relying on the various methods available for hard X-ray image reconstruction, and addressing the uncertainties in the initial TRACE pointing through co-alignment with other data. Each of the issues were critical to the analysis involved and therefore are explained in some detail below.

2.2.1 Event Selection Criteria

We limit the events under consideration through a 3-step process

1. Select flares observed with the flarewatch1600 observing program. This is required to ensure high cadence UV observations (see Section 2.2.2).
2. Verify existence of RHESSI data for the TRACE events selected.
3. Confirm that hard X-ray data contains sufficient counts within the 25-100 keV energy range and covers the entire time range of the flare. This energy range is selected to minimize the thermal emission component in our analysis.

The results of the flare selection are tabulated in Table 2.1. We have a total of eight events covering a wide range of flare classifications. The GOES classification system is explained in 3.1.1. The UV images of these flares show evidence of a number of structural types (single loop, two ribbon, c-shaped, and multiple ribbon flares are all represented) all of which provide different limitations on the magnetic topologies possible in the flaring region. The events of 16 July 2002 and 17 July 2002 provide the focus of the detailed analysis presented in Chapter 3 while the remaining events will be summarized in Appendix A.

RHESSI Flare Number	Date	Time Range (UT)	GOES X-Ray Class
2070405	4 July 2002	07:28-07:35	M 1.1
2070703	7 July 2002	03:57-04:05	C 3.5
2071611 *	16 July 2002	06:36-06:45	C 6.5
2071705 *	17 July 2002	06:56-07:05	M 8.5
2071811	18 July 2002	22:56-23:04	C 8.2
4011911	19 January 2004	12:30-12:38	M 1.1
4111002	10 November 2004	02:03-02:11	X 2.5
4122801	28 December 2004	00:07-00:13	C 7.2

Table 2.1 A summary of dates, times, flare classes, and catalog number for the flares analyzed in this study. (* indicates flare events used in case studies in Chapter 3)

2.2.2 The Flarewatch1600 observing program

The strict requirement of high cadence UV measurements and imaging for this study requires the use of a specialized TRACE observing sequence which eliminates the EUV observations in favor of continual UV continuum observation. The Flare-

watch1600 program is designed specifically to observe flares in the UV continuum. The program works in two phases. During the initial observations of a given field of view, TRACE images a $384'' \times 384''$ field at an approximate 4 second cadence in the 1600Å filter. Every 15-20 images in this mode, TRACE takes a single white light frame. For the pre-flare phases, this provide a white light cadence of ~ 1 minute. When the count rate passes a specified flare threshold, the TRACE field of view reduces to $256'' \times 256''$ centered on the brightest pixel

2.2.3 RHESSI and TRACE Lightcurves

In order to facilitate our temporal analysis, we construct the lightcurves for both the hard X-ray and UV data for each flare studied. Figure 2.2 shows a full-resolution lightcurve from RHESSI data in the 25-100 keV range for one of our flares. The lightcurve shown is emblematic of solar flares and shows transient hard X-ray burst signatures superimposed on the larger scale emission. Aschwanden et al. (1996) have shown that these smaller scale transients are the result of a series of fresh electron injections while the large scale features result from the trapped population. We make no such distinction here as we are interested in the total HXR flux and time history. These large scale bursts provide the basis for our comparison between the UV and hard X-ray emission for both the complete spatially-integrated field of view and the signatures of individual sources.

Comparison of the UV and hard X-ray time profile requires the lightcurves to be

Figure 2.2 Example RHESSI hard X-ray lightcurve from RHESSI flare 2071705 shown at 0.1 second resolution.

of similar temporal scaling. To this end, 2 second resolution lightcurves of the hard X-ray data are constructed. In these curves the small-scale variance of the initial curves are to an extent eliminated due to smoothing effects. However, the large scale bursts similar to those visible in the UV full field lightcurves remain clear. For the cross-correlation analysis with the UV, we rebin the HXR data to 2 second integrated bins to match the cadence provided by the TRACE UV observations. The two-second HXR data which correspond to TRACE image times are then used as a comparative

dataset for cross-correlation with the TRACE full-field observations.

The analysis of the individual source data begins with the source selection performed through the viewing of the TRACE observations in movie form. We discern specific sources which demonstrate clear brightening during the TRACE time frame beginning a few minutes prior to the rise of the hard X-rays. The process used is similar to the full-field lightcurve in that for each selected area we calculate and average count rate per pixel for each frame. The calculated average count rates of each source for each frame present clear evidence of the temporal evolution of the UV response, while the spatial locations of the brightenings provide key comparative data for the UV-HXR relationship and potential visual evidence for the topology of the flare. Similar analysis of individual sources can be done in principle; however, given the integration times required for the X-ray imaging, the individual source lightcurves for the hard X-ray sources would be unable to address the structure shown in the higher time resolution lightcurves.

2.3 TRACE and SOHO/MDI Image Co-alignment

In order to obtain a proper spatial comparison of the UV and hard X-ray source locations, The TRACE pointing must be verified because the metering tube on the spacecraft undergoes minor flexes which cannot be accounted for in the raw positioning data. As a result the TRACE pointing has been shown to be in error by as much as 10 arcseconds. Since, there are no other observations in the UV continuum

available we compare the TRACE white light context images and the MDI white light full-disk intensitygrams. By providing a set of comparable white light images with well defined pointing, the MDI images provide a template for the TRACE image co-alignment. Despite different bandpasses, the TRACE and MDI white light images show similar structures, (e.g. sunspot groups) at different resolutions. A comparative image between the TRACE and MDI data is shown in Figure 2.3. Note that in both images there exist very similar structures which is critical for the co-alignment procedure.

Co-alignment of TRACE and MDI white light images is performed through the IDL-based Solarsoft suite of software with the `trace_mdi_align` procedure. The procedure takes the user defined indices and data arrays, and asks for a region of interest in both the TRACE and MDI data. The user then selects features within the region that appear to be the same structure. This serves as an initial guess for the co-alignment procedure. For the co-alignment of the TRACE and MDI white light images, the timing separation of the images in the 16 July 2002 case shown is 15 minutes. The `trace_mdi_align` procedure then takes the initial guess and calculates the cross-correlation coefficient between the data in the region of interest. From the initial correlation data, the procedure uses an `auto_align_images` program to continually shift the TRACE images until the correlation coefficient reaches a maximum value. A new image center is recorded based on this final shift.

Figure 2.3 Comparative MDI (sub-field) and TRACE white light images for the 16 July 2002 event.

The initial alignment of the white light images for the 16 July 2002 event shows a coordinate shift of approximately 4.7 arcseconds (4.5 in the y-direction and 1.0 in the x-direction) as depicted in Figure 2.4. The magnitude of the shift is typical of the events in this study. The initial white light alignment is then passed through to the UV continuum images via the pointing corrections suggested by Metcalf (2003). The corrected white light coordinates are transferred to the UV image closest in time to

Figure 2.4 Before and after image maps for TRACE (pictured) and MDI (black contours) for the white light image alignment of the 16 July 2002 event.

the initial corrected image, typically 3-4 seconds later. Once a corrected UV image exists, the remaining UV images are aligned with the base image through the same cross-correlation alignment as was used in the white light case. The variations in the central coordinates of the aligned UV images are plotted in Figure 2.5 The alignment results in an average of 3.6 arcseconds with the bulk of the shift being vertical.

To quantify the uncertainties in the co-alignment process, we plot the change

Figure 2.5 Plots of co-aligned XCEN and YCEN coordinate versus image time presented as a demonstration of the effectiveness of the co-alignment process

in the XCEN and YCEN coordinates versus image time (see Figure 2.5). XCEN and YCEN are the recorded central coordinates of the TRACE field of view. We calculate a standard deviation in our results for the coordinates assuming a normal distribution. We determine an uncertainty in the co-alignment of $\pm 2 \sigma$ which for the 16 July 2002 case gives values of ± 1.14 arcseconds for the pre-flare $384'' \times 384''$ images and ± 1.30 arcseconds for the $256'' \times 256''$ images. These data must be considered separately due to the systematic position shift programmed when TRACE goes into flare mode. These results indicate that the co-alignment procedure used is accurate to approximately $1.3''$; thus our co-alignment procedure is sufficiently capable of

correcting the TRACE pointing such that notable separations between the UV and hard X-ray sources are likely the result of flare-related physics and not the alignment procedure.

The descriptions of our datasets and methods above provide all the critical information to conduct our study. In Chapter 3 we apply these procedures to our selected flares and present two in-depth case studies illustrating the viable results of our procedures.

Chapter 3

Analysis and Results

The flares in this study display a variety of responses in the UV and hard X-ray wavelengths. There are 8 events in this study, selected from all available RHESSI and TRACE data spanning a magnitude range of C3.5-X2.5 in the GOES classification system (See Section 3.1). Each event shows a number of unique characteristics, but there are general results to be obtained from the analysis of the events as a group. In order to clearly illustrate the similar traits of these flares, we concentrate on two representative flares as case studies, assigning a summary of the remaining events to Appendix A. The two flares studied in detail are:

- A GOES C6.5 two-ribbon UV event with hard X-ray onset at 06:38 UT on 16 July 2002.
- A multiloop UV event, classified as M8.5, with multiple large scale X-ray bursts from 07:01-07:05 UT. on 17 July 2002

Both of these events occurred in the same solar active region, NOAA AR 10030. For each of the cases we present the results of our temporal correlations with depictions and explanation of the temporal evolution of the flare in both the UV and hard X-rays. For the spatial analyses, comparative images are shown illustrating the spatial location of the resolved sources as they evolve over time. These images permit the

examination of the overall spatial extent of emission in both wavelength ranges as well as the measurement of any notable separation between the UV and hard X-ray sources. Additional work with soft X-ray imaging from RHESSI and magnetogram data from SOHO/MDI permits the investigation of the overall X-ray structure and the magnetic field topologies potentially responsible.

3.1 The 16 July 2002 event

3.1.1 Event Overview

Figure 3.1 Plot of the time sequence of GOES soft X-ray data for 16 July 2002 from 00:00-12:00 UT. The flare we are interested can be seen between 06:30 and 08:30 UT

The 16 July 2002 event in our study is classified as a C 6.5 flare based on the GOES soft X-ray data. The flare peaks in the soft X-rays at 06:42 UT (see Figure

3.1). The GOES X-ray classification is defined by flux measurements in the 1-8 Å wavelength range on a log scale. The classes are defined as shown in Table 3.1. This event's size is small in comparison to many flares in other studies; however even in this small event, there exists tremendous temporal and spatial detail that provides an excellent test dataset to address the UV/HXR relationship. The GOES soft X-ray

GOES Flare Class	Flux Range (W/m ²)
A	$< 10^{-7}$
B	10^{-7} - 10^{-6}
C	10^{-6} - 10^{-5}
M	10^{-5} - 10^{-4}
X	$> 10^{-4}$

Table 3.1 The GOES flare classification system based on 1-8 Å fluxes during the peak of the flare

profile of the event illustrates the overall temporal behavior of the flare in the soft X-rays, which typically traces thermal emission. This allows us to quickly compare different flares. However, only the hard X-ray timing is critical for our study. The initial inspection of the RHESSI data for the 25-100 keV energy range (Figure 3.2) shows predominately a single large scale burst over the time frame of 3.5-4 minutes. The single burst has a number of smaller scale events on the time scales of a few to tens of seconds. These small scale events become clear as secondary bursts when the data is smoothed to match the cadence of the UV data. We focus on the period of hard X-ray emission from 06:39:30-06:43:00. We find a steep rise representative of

Figure 3.2 RHESSI hard X-ray lightcurve for an energy range of 25-100 keV from flare 2071611 shown at 0.1 second resolution for the time range 06:39:10-06:43:10. (Smaller time range shows the available times for reliable data)

the impulsive phase of the event leading to a peak at $\sim 06:40:25$ UT approximately one minute after flare hard X-ray initiation, followed by a consistent decay until 06:43 UT. From Figure 3.2 we see that the larger overall structure is comprised of separate burst structures. The first burst which is smaller in amplitude appears from 06:39:30-06:40:05 with a peak at 06:40:00 UT while the subsequent burst containing the peak of emission begins at 06:40:10 and continued until 06:40:40.

The overall UV time evolution is obtained from spatial integration of the full

TRACE field of view; however, to take into account the varying area of the field of view in the TRACE observations, we present the data as an average count rate per pixel. The overall UV profile is predominately defined by several burst periods, many of which show similarities to the HXR response (see Figure 3.3).

Figure 3.3 Imaged lightcurve results from the TRACE 1600Å data. A number of clear burst structure are visible in the data which will serve as time frames of interest. The vertical line at 06:39:52 denotes when TRACE flare mode initiated.

Three bursts are evident in the UV profile over the time range 06:39:30-06:41:00. Two considerably smaller bursts are evident over the next minute. The three large bursts during the first interval show similar duration and relative counts to those within the hard X-ray data. We quantify these observations through cross-correlation analysis for both the full field of view and the individual selected sources presented in Section 3.1.2.

Spatial observations of the 16 July 2002 event in the UV continuum depict a flaring region containing two widely separated ribbons. The top ribbon brightens in segments and covers an area of $85'' \times 45''$ but at any given time is varied in extent and appearance. In contrast, the lower ribbon is consistent in extent; however, there are variations in brightness from the two endpoints of the ribbon over time. The western endpoint shows significant brightening both prior to and following the hard X-ray activity. The majority of the UV activity in the lower ribbon during the hard X-ray emission is concentrated near the left (eastern) endpoint. A sequence of TRACE UV images depicting the evolution of the UV ribbons is displayed in Figure 3.4. The upper ribbon of the UV evolves as a series of four sources during the HXR activity beginning at the upper right of the ribbon and progressing over time closer to the center of the ribbon's extent. The eastern side of the upper ribbon displays an extended emission of approximately $25''$ in length which is evident before and after the bulk of the X-ray activity but is not visible during the X-ray period.

In contrast to the widely spaced UV ribbons, RHESSI images for the energy range 25-100 keV depict a compact region of the hard X-rays. This strong hard X-ray region is confined to an area of $20'' \times 10''$ and is occasionally separable into two distinct footpoints within this confined region. In relation to the UV emission, the hard X-ray sources imaged (centered at $[31'', 230'']$) are located near the east end of the lower UV ribbon. Figure 3.5 illustrates the development of the hard X-ray sources

Figure 3.4 TRACE UV image sequence illustrating the evolution of the UV ribbons over time. Note that the lower ribbon is very well defined throughout while the upper ribbon is not very well defined for a early portions of the sequence.

over the course of the X-ray emission period.

The hard X-ray source described above is the strongest source defined through the Pixon image reconstructions. The 20-second integrated images indicate a weak but detectable source near the spatial location of the upper UV ribbon. The implication of these source locations and strengths will be addressed in Chapter 4

Figure 3.5 Four RHESSI Pixon images with 20 second time resolution covering the time range 06:39:40-06:41:00. These images show a strong HXR source low in the field of view while a secondary weaker source is evident in the north of the field of view and some evidence of a weak connection between the two at later times.

3.1.2 Temporal Analysis Results

The general description of the event observations discussed in the previous section suggests qualitatively a temporal link between the overall behavior similar to that found in prior studies (Cheng et al., 1988) as well as interesting developments regarding the evolution of the UV source emission relative to the hard X-ray emission. In an attempt to quantify the significance of these timing similarities, we present the

results of cross-correlation analysis performed both on the overall UV response with respect to the hard X-rays and the individual UV source responses with the total hard X-ray data. This provides insight into the overall relationship while also addressing the significance of the hard X-ray production as a factor in the UV source evolution.

Full-field correlation analysis

In the previous section, the general behavior in both the hard X-rays and the UV emission are displayed in their raw form. The hard X-ray data is displayed in the form of a 0.1 second resolution lightcurve while the UV results are displayed as a pixel averaged lightcurve with the two second resolution of the TRACE images. Though qualitative similarities are evident, it is difficult with the different time scales and the transient behavior in the hard X-ray to clarify and quantify these results. To aid in the correlation study we have rebinned the RHESSI data in 2 second bins to mimic the TRACE cadence. Once both data sets are of similar cadence, both lightcurves are normalized and overplotted for visual comparison as shown in Figure 3.6. We know the single data point spike near 06:39:10 UT, is the result of an uncorrected attenuator change by RHESSI at or just before the time of that measurement. This is a purely instrumental artifact and not a reflection of actual hard X-ray activity. Both linear and Spearman rank correlation coefficients are calculated for the time

Figure 3.6 Scaled lightcurve plot for the hard X-ray data at 2 second resolution (upper) with an overlay of the normalized UV data (lower, scaled to a maximum of 0.3 for clearer visual comparison).

frame. We calculate the linear correlation coefficient equation 3.1:

$$r = \sqrt{\frac{\sum(x - \bar{x})(y - \bar{y})}{\sum(x - \bar{x})^2 \sum(y - \bar{y})^2}} \quad (3.1)$$

where $\bar{x}$ and $\bar{y}$ are the mean values of the the RHESSI and TRACE normalized datasets and x and y are the respective normalized data values. For the rank coefficient we apply a similar technique; however, instead of the actual data values, each value is given a numerical rank in ascending order. The rank correlation coefficient is then calculated from equation 3.2:

$$r = \sqrt{\frac{\sum(Rx - \bar{Rx})(Ry - \bar{Ry})}{\sum(Rx - \bar{Rx})^2 \sum(Ry - \bar{Ry})^2}} \quad (3.2)$$

where $\bar{R}x$ and $\bar{R}y$ are the mean ranks of the datasets. Along with the correlation results, we also include the false alarm probability, which is the probability that a given correlation could result from uncorrelated, random data. The smaller values of the false alarm probability indicate a stronger correlation. Acknowledging an instrumental data spike and noting that the primary X-ray onset begins at approximately 06:39:30, we also perform correlation calculations on this time interval including the fall-off until 06:43:00. The results of these calculations are provided in Table 3.2. The datasets show a strong overall correlation with correlation coefficients over the time frames discussed ranging from $r=0.858$ to $r=0.925$. Although the overall behav-

Time Range (UT)	Method	Coefficient	P_{FA}
06:38:00-06:43:00	Linear	0.858	1.66×10^{-38}
06:38:00-06:43:00	Rank	0.910	0.00000
06:39:30-06:43:00	Linear	0.879	6.93×10^{-35}
06:39:30-06:43:00	Rank	0.925	4.20×10^{-45}
Individual Burst Correlations			
06:39:30-06:40:10	Linear	0.848	1.69×10^{-5}
06:39:30-06:40:10	Rank	0.841	7.72×10^{-4}
06:40:10-06:40:40	Linear	-0.128	0.640
06:40:10-06:40:40	Rank	-0.091	0.737

Table 3.2 Full-field correlation results for the overall observation period as well as the individual bursts seen in the temporal profile. P_{FA} is the false alarm probability of the correlation reported resulting from random data.

ior shows strong correlation for the complete time frame, the analysis of individual bursts is less definitive. The correlation results indicate strong correlation with the initial burst from 06:39:30-06:40:10 with correlation coefficients of 0.841 and 0.848

depending on the method employed. The second much larger burst does not show a meaningful correlation; however, that there are similar structures visible.

Individual Source Evolution

Although the overall UV temporal profile is well-correlated with the overall hard X-ray behavior, the UV emission demonstrates significant temporal evolution within the two visible ribbons while the hard X-ray emission remains well-defined with similar structures throughout. The lower ribbon is more sharply defined throughout the observations while the upper ribbon is more extensive but appears as more of a loose collection of sources rather than a solid ribbon. For each of the complete ribbons,

Figure 3.7 TRACE 1600 Å image depicting the extent of the two visible ribbons structures

we compare their lightcurves with the 2-second averaged HXR emission, as we have

done previously for the complete field, to determine to what extent the separate UV ribbon emission is correlated with the X-ray activity. The lightcurve plots for both ribbons are shown in Figure 3.8.

Figure 3.8 Plot of normalized HXR lightcurve overlaid with the TRACE lightcurves for the upper UV ribbon (left plot) and the lower ribbon (right plot)

The UV ribbon plots demonstrate clear differences in the temporal behavior of the ribbons. Since each UV point has been scaled to the same value (normalized to the maximum value regardless of ribbon and scaled by 0.3), an immediate observation is that the upper ribbon is markedly more active relative to the lower UV ribbon. The lower ribbon, at its brightest point, is only 53 percent of the brightest overall UV

emission, and this maximum occurs early in the time frame relative to the hard X-ray bursts; thus, the data indicate that the upper ribbon is the more closely associated with the bulk of the hard X-ray activity. The relative strengths of the ribbons along with their spatial location raises interesting spatial comparisons with the determined location of the X-ray sources from the RHESSI images. The spatial comparisons will be elaborated upon in Section 3.1.3. Also of note from Figure 3.8 is the difference in correlation significance in the two cases. Correlation results over the entire time frame for both ribbons display the previously shown whole flare correlation but to limited degrees. The linear correlation coefficients calculated for the upper and lower UV ribbons were 0.838 and 0.664 respectively (Results for the Spearman rank correlation are 0.919 and 0.619 respectively). The correlation calculation for the upper ribbon confirms the similarity with the overall behavior qualitatively apparent through comparison of the lightcurves. This further emphasizes the dominant association of the upper ribbon with the hard X-ray time profile

Although the upper ribbon appears dominant in the overall temporal profile, it is of interest to compare the correlations of each ribbon with the individual HXR burst as was done with the overall case. These results are shown in Table 3.3. The upper ribbon is moderately well correlated with the overall HXR emission in all cases except for the time frame including the second burst from 06:40:10-06:40:40. The lower ribbon, however, shows a slight correlation with the second burst (coefficient

Time Range	Method	Ribbon 1	Ribbon 2	P_{FA1}	P_{FA2}
06:38:00-06:43:00	Linear	0.838	0.664	3.08×10^{-35}	9.49×10^{-18}
	Rank	0.919	0.619	0.0000	5.53×10^{-15}
06:39:30-06:43:00	Linear	0.855	0.650	4.15×10^{-31}	6.41×10^{-14}
	Rank	0.918	0.498	3.97×10^{-43}	3.58×10^{-7}
06:39:30-06:40:10	Linear	0.775	0.397	2.58×10^{-4}	0.115
	Rank	0.730	0.456	0.00348	0.0682
06:40:10-06:40:40	Linear	0.107	0.570	0.684	0.021
	Rank	0.186	0.574	0.456	0.0241

Table 3.3 Complete correlation results for the two UV ribbons. For each correlation calculation, we also supply the false alarm probability.

0.474) To summarize the results of the ribbon analysis: The overall temporal profile of the ultraviolet emission is primarily governed by the emission in the northern ribbon with a smaller contribution (in terms of count rates) produced in the southern ribbon. The southern ribbon's most prominent contribution occurs both during the early impulsive rise of the initial burst at which time the second ribbon takes its maximum value, and then makes a minor contribution co-temporal with the peak of the hard X-rays and during the second burst of the hard X-ray emission. The hard X-ray emission is confined to a loop which is near the left end of the southern UV ribbon.

Because of the apparent fragmentation of the upper ribbon and the fluctuations of the endpoints of the well-defined southern ribbon, another aspect of the temporal behavior we investigate is the behavior of the individual kernels within these ribbons as it relates to the overall timing correlation as well as the behavior during notable X-

ray bursts. In analyzing the individual sources, we apply the source selection process described in 2.2.3. In the northern ribbon, we find that the ribbon is separable into four main kernels each of which brighten initially in a progression from the the northern and western extent (Box 1) of the ribbon dropping to the south and east(Box 4). Figure 3.9 illustrates the selected sources analyzed for this portion of the study. Upon source selection, we then generate the UV lightcurves for the

Figure 3.9 TRACE UV image frame depicting the the selected sources uses in the individual kernel analysis.

kernels and compare the temporal development with that of HXR data. We perform correlation analysis on the respective bursts when the sources are active.

Lightcurves for the individual kernels in the northern ribbon are overlaid onto the overall HXR time profile in 3.10. Upon examination of this composite lightcurve,

Figure 3.10 Composite lightcurve showing sources 1 through 4 in relation to the overall normalized hard X-ray curve (Normalized UV scaled by 0.4 for comparison.). Sources 1 through 4 are plotted with increasing thickness.

contributions of the specific sources are clearly discernible. Among the interesting behavior of the kernels, source 1, in the northwest corner of the ribbon, brightens and dims during two distinct periods. Brightening occurs with this source early in impulsive rise of the HXR data; however, this initial brightening falls off at the onset of

the initial HXR burst. Source 1 does not contribute significantly again until 06:41:20 after both significant bursts of HXR emission. Thus, source 1 is largely uncorrelated with the HXR data despite being a notable source of UV emission during the time frame of interest. In contrast, sources 2 and 3 show their largest contributions during the initial burst of the hard X-ray emission. Both the visual and lightcurve evidence indicates that the brightest of these sources is Source 2 which also is the first to activate. As Source 2 reaches its peak the emission begins in earnest in region 3. Due to the source selection process using rectangular areas, there is an overlap between regions 2 and 3. However, the emission in the visual inspection demonstrates that the two regions enclose predominantly separate brightenings. Following the initial burst of the HXR emission, emission from these two UV sources slowly diminished and did not show appreciable increase during the second HXR burst. As with the overall field and complete ribbon cases this peak of the hard X-ray data is not clearly evident in the UV emission. The UV which appears near the second burst of hard X-rays is dominated by strong emission from source 4 in the southern portion of the top UV ribbon. Source 4 in this peak is the strongest UV emission recorded overall. We will address the specific correlations of both UV ribbons simultaneously after addressing the behavior of the southern ribbon sources.

The southern ribbon of ultraviolet emission is dominated by emission contained within the two endpoints (see Figure 3.11). The western endpoint (source 6) shows

Figure 3.11 Normalized source lightcurves (scaled by 0.4 for comparison) for the sources in the southern ribbon overlaid against the normalized X-ray emission. Source plot colors are as follows: source 6: middle curve and source 7: lowest curve

similar behavior to that of source 1 in the upper ribbon in that it produces the majority of its UV emission both prior to and following the hard X-ray emission. This similarity will be addressed later as a discussion of potential conjugate emission. As far as emission that is predominantly co-temporal with the hard X-ray emission peaks, the lower ribbon's contribution appear to be confined to source 6 at the eastern end of the lower ribbon. The emission profile of source 6 shows similarities to the X-ray behavior although the peak of the UV emission for source 6 precedes the two prominent hard X-ray bursts; however, the profile also demonstrates a rise in emission

at each burst of the HXR profile which does not reach the value of the earlier peak.

A discussion of correlation results with all of the individual sources follows below.

Figure 3.12 UV emission profiles for the 4 sources of the upper UV ribbon each scaled to 0.4 of normalized count rates and overlaid onto the normalized HXR profile.

For the correlation analysis of the individual sources we analyze the time frames in which each source is clearly active in relation to the HXR emission. The times used can be inferred for the upper ribbon sources from the profiles shown in Figure 3.12. Source 1 produces, at its peak, only ~ 20 percent of the maximum UV emission. The emission from this source occurs from 06:38:40-06:39:40 and then reoccurs from 06:41:30-06:42:30.

Correlation results for source 1 over these time interval confirm the hypothesis of a minimal correlation with the hard X-ray emission. Source 2 shows emission activity over the time frame 06:39:00-06:42:00. The peak emission of this region covers 06:39:50-06:40:30. This is the time frame in which the bulk of the HXR bursts occur. All correlation results for the individual sources with respect to both the overall and individual burst behavior are included in Tables 3.4 and 3.5. The

Time Range	UV Source	Linear	Rank	P_{FAL}	P_{FAR}
06:38:40-06:39:40	Source 1	0.429	0.777	0.086	1.88×10^{-3}
06:41:30-06:42:30		0.191	0.295	0.296	0.101
06:39:00-06:42:00	Source 2	0.657	0.792	2.60×10^{-11}	1.27×10^{-18}
06:39:50-06:40:30		0.223	0.183	0.330	0.413
06:39:50-06:40:10		0.702	0.700	0.016	0.027
06:40:10-06:40:30		0.461	0.482	0.154	0.128
06:40:00-06:42:00	Source 3	0.520	0.775	1.05×10^{-5}	5.15×10^{-14}
06:40:00-06:40:10		0.292	0.643	0.525	0.115
06:40:10-06:40:30		0.722	0.700	0.012	0.027
06:40:20-06:42:00	Source 4	0.923	0.820	8.69×10^{-23}	6.05×10^{-14}
06:40:20-06:40:50		0.912	0.891	8.81×10^{-7}	3.62×10^{-6}

Table 3.4 Correlation results with false alarm probabilities for the UV sources of the upper ribbon for times of significant activity in either UV or hard X-ray emission.

Time Range	UV Source	Linear	Rank	P_{FAL}	P_{FAR}
06:39:00-06:42:00	Source 5	0.635	0.714	1.25×10^{-10}	4.93×10^{-14}
06:39:40-06:40:10		0.251	0.358	0.386	0.196
06:40:10-06:40:40		0.451	0.517	0.069	0.039
06:38:40-06:39:40	Source 6	0.559	0.784	0.020	0.017
06:41:30-06:42:30		-0.377	-0.254	0.033	0.153

Table 3.5 Correlation results with false alarm probabilities for the UV sources of the lower ribbon for times of significant activity in either UV or hard X-ray emission.

correlation results presented here illustrate the spatial variation of the UV emission. Focusing on the bursts detectable in the overall X-ray profiles, it is evident that there are multiple active UV sources during these X-ray bursts. Source 2, and to a lesser extent source 3, shows a good correlation with the data of the initial burst while the second burst is well-correlated with sources 3 and 4. Emission in this ribbon during the hard X-ray burst is dominated by emission from source 5 at the eastern end of the ribbon. This emission shows a moderate correlation with the hard X-ray emission during the second burst of the hard X-ray profile but it is active throughout. In Section 3.1.3, we will address the spatial locations of both the X-ray and the UV sources of both ribbons during each of these correlated time frames.

The potential for conjugate footpoints in the UV emission, independent of the hard X-ray data, provides critical insight into the connectivities permitted in the flaring region. Conjugate footpoints are defined as spatially separate emission sources showing correlated time profiles. The sources are often but not exclusively believed to be the footpoints of active flare loops. The sources active during the hard X-rays bursts do not show conjugate activity; however, sources 1 and 6 which display predominantly pre-flare and post-flare emission have time profiles which suggest the possibility of conjugate activity. The profiles for these sources are shown in Figure 3.13. Both linear and Spearman rank correlation indicates a moderate to strong correlation in the data for these sources yielding correlation coefficients of 0.699 and

Figure 3.13 Normalized UV emission from source 6 in the lower ribbon (upper curve) with overlay of relative UV emission from source 1 in the upper ribbon (lower curve -scaled by 0.5 for easier viewing)

0.831 respectively. This is significant evidence though not confirmation of conjugate activity. The implication of conjugate footpoints from these two sources suggests a magnetic connection between the sources which would need to be incorporated into our flare depiction included in Chapter 4. We will address further the effects of the conjugate activity at that time.

3.1.3 Spatial Analysis

In the previous section, we determined that on a number of levels the temporal profiles of the UV and hard X-ray emission were strongly correlated. The correlated

emission implies that the UV and hard X-ray sources are governed by the same energy input mechanism. Beyond the temporal correlation, it is critical to physical understanding of the flare to determine the spatial locations of these well correlated emissions as the spatial differences may imply increased complexity of the flaring structures. Using imaged data from both TRACE and RHESSI, we have been able to spatially localize the emission sources for both the UV and hard X-ray wavelengths over the majority of the flare duration. In this spatial analysis, we will focus on the spatial distribution of emission for the periods of greatest activity from the temporal profile. The high cadence of the UV observations and short integration times (10 seconds for this event) allow us to track the evolution of the emission during these intervals of peak emission.

Our initial interval for spatial analysis focuses on the time frame near the initial burst of the hard X-ray emission from 06:39:40-06:40:00. This interval allows for the comparison of the spatial locations of the emission as the time profile reaches its initial peak from its rise until its weak decay. Figure 3.14 presents a series of UV image maps with the contours of the hard X-ray images. Due to the initial low counts in the X-ray data, we choose to integrate over a 20 second interval to permit image reconstruction convergence.

The observations depict the strongest hard X-ray emission for this period as a tightly confined source with its centroid at approximately $[30'', 231'']$. This spatial

Figure 3.14 Series of TRACE 1600 Å images with contours from RHESSI X-ray image integrated from 06:39:40-06:40:00. The contours shown represent X-ray emission levels of greater than 50 percent of the maximum recorded.

location is approximately 2 arcseconds from the center of the UV source on the eastern side of the lower ribbon of UV emission. In contrast, there is no well-defined X-ray source of similar strength corresponding to the upper ribbon of UV emission. Though we cannot specifically rule out hard X-ray emission in this upper ribbon, it is worth noting the RHESSI image contours at levels as small as one-tenth of the maximum show no such emission in region indicating that an X-ray source within the upper ribbon is at most one-tenth as strong as the source defined in the lower ribbon. *From the temporal ribbon analysis earlier, we found that the northern ribbon was the ribbon most correlated with the hard X-ray emission yet the hard X-rays appear in the data co-spatial with the southern ribbon. The spatial separation between the upper UV*

ribbon and the hard X-ray sources is ~ 65 arcseconds ($\sim 50,000\text{km}$).

The observations included in Figure 3.14 demonstrate aspects of the UV evolution discerned from the timing study. In the initial image, an upper source on the northern UV ribbon (Source 1 of the temporal study) and a notable source on the western side of the of the lower ribbon (source 6) produce significant emission; however, in the subsequent images, minimal emission is found for these areas consistent with the timing discussed previously. As the upper ribbon UV sources activate, the emission appears to progress down the ribbon while the X-ray and lower ribbon emission remains well-confined (see Figure 3.15 for evidence during peak hard X-ray emission) throughout the periods of greatest activity. As the X-ray counts rise, two sources which represent potential footpoints of a hard X-ray loop become more clearly defined. This potential X-ray loop is still well-confined to a $20'' \times 20''$ region. In contrast the UV sources continue to brighten sequentially down the upper ribbon until its maximum brightening in the lower center of the ribbon (source 4 of the timing study).

We know from the timing implications described previously that these separated sources must still be governed by the same initial energy release from the magnetic reconnection responsible for flare initiation. One of the implications of this separation is the implied necessity of a complex multiloop structure in order to achieve both the temporal development shown while maintaining the spacing and apparent progression of emitting sources. The dominant X-ray sources at the peak of emission are depicted

Figure 3.15 TRACE UV maps for the time frame 06:40:00-06:40:20 with contours overlaid depicting the hard X-ray emission imaged by RHESSI. The contours shown contain all hard X-ray points greater than 30 percent of the maximum image value.

as two tightly confined footpoints signifying as a part of the connectivity of the overall flare region at least one simple loop connecting the two footpoints. The inclusion of soft X-ray observations discussed at length in Chapter 4 reveals a long thermal loop connecting the the two ribbons of UV emission and providing a crucial connectivity and second loop for the multiloop scenario. The temporal connection between the bulk hard X-rays and the UV emission raises several magnetic connectivity questions. The lower ribbon of UV emission during the time frame of X-ray emission is essentially co-spatial with the dominant hard X-ray data at the eastern side of the ribbon. The most notable complication is the need to reproduce and explain the fragmented ribbon

development of the correlated UV emission down the upper ribbon. This suggests a interacting loop which must account for the progression of UV brightenings down the ribbon. Each of the structures discussed here would also have to connect to a reconnection site believed responsible for the flare initiation. A further explanation of this connectivity picture and its implications will be addressed further in Chapter 4.

3.2 The 17 July 2002 event

3.2.1 General Observations

The 17 July 2002 event in this study is classified as M8.5 flare with notable hard X-ray emission observed from 07:01:00-07:05:00 UT. This event originates from the same active region responsible for 16 July 2002 event previously discussed. As an M8.5 flare, the peak emission of this event is approximately 13 times as intense in soft X-ray emission as the 16 July event.

Similar to the GOES plot for the 16 July event, the soft X-ray profile depicts a single impulse; however, as would be expected with a larger flare, this profile indicates a more energetic event with a longer duration.

Though the GOES profile shows a single impulse, examination of the hard X-ray profile shows a intense hard X-ray envelope from 07:00:00-07:04:10 UT. Within this time frame, we see four notable bursts of hard X-ray activity of varied duration. The HXR profile shown has been binned to 2 seconds and shows a number of similarities

Figure 3.16 GOES 1-8Å soft X-ray plot depicting an M8.5 event on 17 July 2002 recorded in the GOES data from 06:58-07:19 UT.

with the previous event, the increased number of bursts and longer duration, however, provide evidence of additional complexity typically expected in larger events. Aside from the overall UV/HXR correlation, with this event we will focus on three intervals during the emission. The two primary bursts occur from 07:01:30-07:02:40 and 07:02:40-07:03:20 respectively. A lesser burst from 07:03:20-07:04:20 will also be examined. Unfortunately, the small preliminary burst from 07:00:50-07:01:30 cannot be studied from a correlation perspective due to a data gap in the UV data from TRACE during that interval.

The nature of the ultraviolet data for this event in terms of timing is described by

Figure 3.17 Hard X-ray (25-100 keV) lightcurve at 2 second resolution for the time range 06:59:00-07:05:00 UT

its own series of burst-like emission; however, an overall envelope is not as evident as it is in the hard X-ray data. During the prominent rise of the X-ray data, the UV data follows suit producing its most intense emission. Though there is not a coincident hard X-ray peak during the peak emission, this is a similar rise for comparison. The relative fluxes of the UV and HXR bursts themselves are not a part of this study as they have more to do with ambient and transport conditions than the time signatures

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Figure 3.18 Imaged lightcurve created from TRACE observations of the flare event from 06:56-07:05 UT. Note the predominate burst-like nature of the UV emission.

of the energy release.

The subsequent HXR burst in the observations from 07:03:20-07:04:20 is nearly mirrored by the UV emission. We will quantify these observations in the next section. The burst structure of the UV profile, indicates a maximum response to the initial flare energy release during which the greatest measured UV response for this flare is recorded. Subsequent bursts are reflected in the profile but their recorded count rates reflect the reduced response of the UV data.(see Figure 3.18).

Spatially, the UV emission is dominated by two extended ribbons in which a number of smaller active components illuminate throughout the time series. A third ribbon appears near the end of the observation period; however, its significance to the overall behavior is dominated by the two larger ribbons. A time sequence of the

UV images is provided in Figure 3.19. As the emission develops, the primary ribbons

Figure 3.19 Representative image sequence of the 17 July 2002 flare UV observations showing two well-defined dominating the majority of emission.

become evident almost immediately, and reach their brightest emission in the observations at 07:01:24. As the observations continue through the time profile, the initial brightening of the ribbon component in unison is replaced by a more fragmented emission while still maintaining the overall ribbon structure. Approximately 90 seconds after the flare initiation, the third UV ribbon becomes visible. This does not preclude the third ribbon's activity during the initial bursts; however, any activity from this

Figure 3.20 Sequence of RHESSI hard X-ray images (taken at 5 second integration) depicting the spatial orientation of the 25-100 keV X-rays as they evolve during the flare.

Spatially, the hard X-ray emission in the 17 July 2002 event is considerably more complex than what was seen in the prior event. Because this is a larger flare, we expect a level of added complexity. The hard X-ray images from RHESSI show the development of two sets of hard X-ray footpoints leading to the description of two hard X-ray loop structures which persist through the duration of the flare period (Figure 3.20). Because this is a larger flare, the X-ray sources are successfully imaged with less integration time due to the increased count rates available compared to the

prior event. A more comprehensive explanation of the spatial behavior of this flare is included in Section 3.3; however, it is worth noting from the X-ray overview the existence of well-defined X-ray sources for the entire duration of the time profile.

3.2.2 Temporal Results and Discussion

The temporal development within the 17 July 2002 event is similar in many respects to the overall behavior of the previous event discussed; however, the individual source development and increased spatial complexity present a number of differences which must be described to determine more general flare results. To this end, we simply summarize the similarities since the analysis approach was detailed in the prior discussion (Section 3.1.2) and focus primarily on the complexities which make this event worth considering in some detail

Full-Field Correlation Results

The temporal profile in hard X-rays of the 17 July 2002 event depicts an envelope of X-ray emission from 07:00-07:05 UT. Within this emission envelope there are four notable bursts (07:00:00-07:01:30, 07:01:30-07:02:40, 07:02:40-07:03:40, and 07:03:50-07:04:30); however, there are only three for which we can perform a correlation analysis. The initial burst cannot be effectively addressed because of a approximately one-minute data gap in the TRACE observations which spans the majority of this initial burst. The results of this work are displayed in Table 3.6. The results

Figure 3.21 Normalized RHESSI lightcurve for the complete duration of the observation period with the TRACE observation lightcurve (scaled to 0.4 of the normalized values for comparison)

presented along with the study of the overall profile indicate a moderate correlation of the overall full-field data and the RHESSI observations. Using the full-field data results in a correlation of 0.512; however, focusing on specific bursts provides a significant variation in the effective correlation of the UV brightenings in relation to HXR bursts. The correlation is clearly strongest during the final burst late in the flare. Like the previous event, the stronger central burst of the hard X-ray emission shows a weak to moderate anti-correlation as the UV emission decreases significantly at this time. This event shows an interesting behavior of significant correlation at the onset and near the end of the emission, while the central Hard X-ray emission is largely uncorrelated. We investigate this occurrence further by looking at the individual

Time Range (UT)	Method	Correl. Coeff.	P_{FA}
07:00:00-07:05:00	Linear	0.358	7.37×10^{-5}
	Rank	0.512	5.96×10^{-8}
07:01:30-07:02:40	Linear	-0.286	0.0903
	Rank	-0.375	0.0264
07:02:40-07:03:20	Linear	0.598	4.44×10^{-3}
	Rank	0.526	0.0187
07:03:40-07:04:30	Linear	0.792	1.42×10^{-6}
	Rank	0.838	2.80×10^{-5}

Table 3.6 Correlation results for the Full-field TRACE time profile and the two-second integrated RHESSI profile.

correlation of separable sources contained on the three UV emission ribbons.

UV Source Analysis

Separating the UV emission into individual sources, we isolate eight sources in total selecting regions of active emission along the three ribbons in the flaring region. The selected regions are displayed in Figure 3.22. Since the eight sources are located on three distinct ribbons, we have broken the overlaid comparison into three images each reflecting only sources specific to a given ultraviolet ribbon (see Figure 3.23. Each of the UV curves is scaled by the same value so that relative strengths can be discerned for the graphical comparison. From these data and lightcurve comparisons, the most active UV source is source 5 near the top of the center ribbon. This source remains active throughout and displays a number of similar structures to those visible in the X-ray profile. However, during the peak of the hard X-ray emission, source 5 does not correlate well. The predominant sources during the most intense peak of the

Figure 3.22 TRACE observation image depicting the eight selected source regions for the 17 July 2002 event

X-rays are UV sources 1 and 2. This indicates that the majority of the UV emission in response to this peak emanates from the leftmost ribbon. As is visible in the images, the third ribbon is a much weaker contributor to the overall behavior than the two primary ribbons, its only major contribution occurs between 07:02:00-07:02:40 and at its maximum was only 25 % of the maximum UV emission. The correlation results for the specific UV emission sources over the times of their notable activity are shown in Table 3.7.

The correlation results when viewed alongside the profiles indicates that for the

Figure 3.23 Overlaid UV source lightcurves for each individual source atop the hard X-ray lightcurve from RHESSI. Sources are plotted based on ribbon location (Sources 1-4: left, Sources 5-6: middle, and Source 7-8: right). The UV data is scaled to 0.6 of normalized values

two primary ribbons, which are continually active throughout the duration of the X-ray emission, the emission levels of each ribbon seems to depend on the other. For the period when the leftmost ribbon (particularly sources 1 and 2) reaches its peak emission levels, Sources 5 and 6 of the central ribbon emission drop to their minimum flare levels. Likewise similar behavior is exhibited by the left ribbon when sources 5 and 6 emit levels of increased emission, sources on the left ribbon show their minimum levels. Source 5, being the most active source throughout has been moderately correlated with two bursts of X-ray emission for 07:02:10-07:02:40 and 07:03:30-07:04:10. The sources in the central ribbon show their most significant activity, however, dur-

UV source	Time (UT)	Linear	Rank	P_{FAL}	P_{FAR}
Source 1	07:02:40-07:03:20	0.639	0.584	1.81×10^{-3}	8.96×10^{-3}
Source 2	07:02:40-07:03:20	0.628	0.669	2.30×10^{-3}	2.78×10^{-3}
Source 3	07:01:30-07:02:10	-0.391	-0.431	0.0795	0.0538
Source 4	07:01:30-07:02:10	-0.051	-0.008	0.827	0.972
Source 5	07:03:30-07:04:10	0.379	0.562	0.0906	0.0119
	07:01:30-07:02:10	0.051	0.043	0.8245	0.8480
	07:02:10-07:02:40	0.471	0.447	0.0652	0.0834
	07:03:30-07:04:10	0.563	0.647	7.94×10^{-3}	2.58×10^{-3}
Source 6	07:01:30-07:02:10	-0.532	-0.555	0.0130	0.0131
Source 7	07:02:00-07:02:50	-0.317	-0.278	0.1148	0.1646

Table 3.7 UV source correlation results for periods of noteworthy source activity

ing the time frames just following the initial X-ray burst brightening near 07:01:30. This bright emission and its subsequent decay render the UV emission in the time range 07:01:30-07:02:10 as uncorrelated with the HXR emission. In fact two of the weaker sources, source 3 and source 6, show a significant degree of anticorrelation due to the rapid UV emission drop while the HXR data continues a significant rise in emission. The lightcurve analysis indicates UV emission at the peak of the hard X-rays is concentrated in the left ribbon. The locations of these brightenings relative to the hard X-ray sources present a similar spatial challenge to that discussed in the prior flare.

3.3 Spatial Description and Analysis

In the general description of this event, we briefly addressed the additional complexity often seen in more energetic flare events. The RHESSI images shown in Figure

3.20 provide a clear example in comparison with the previous event. These images, taken with shorter integration time (5 seconds), resolve a number of strong hard X-ray sources which are widely separated in the chromosphere. As we progress through the both the UV and hard X-ray observations we find that the UV emission is contained in more extended ribbons while the hard X-ray are more localized the UV counterparts. The hard X-ray emission shows a great deal of variability in location of its brightest sources which appear in these observations to also be reasonably consistent with the timed brightenings in the ultraviolet. It is necessary to note however the number, orientation, and strength of the localized X-ray sources varies dramatically with time as evident in the image series (see Figures 3.24 and 3.25).

The initial sequence of images covers the highest peak of the UV emission near 07:01:30 along with its subsequent decay. During such time the X-ray emission continues to increase. As time progresses through the period of the second burst of HXR emission from 07:02:10-07:02:40, we see similar spatial development in both the hard X-rays and the UV as both emissions become more strongly concentrated in the left ribbon while the right ribbon emission slowly declines until such time as X-ray emission is minimal (07:03:00). The emission variability indicates a strong connection between the UV and hard X-ray emission in this flare in terms of both temporal behavior and spatial emission. In this flare there is a much smaller separation between the UV emission ribbons and the corresponding X-ray sources. This is a direct

Figure 3.24 Sample sequence of TRACE images from 07:01:30-07:02:40 with 25-100keV X-ray contours from the RHESSI image reconstructions.

contrast to the 16 July 2002 event where the most correlated UV sources were widely separated from their X-ray counterparts. A similar consolidation occurs in the later stages of the flare emission as it becomes concentrated in the right ribbon. The X-ray strength is reduced from the prior burst emission, consistent with the temporal profile; however, the contribution is still significant.

Though the emission in both hard X-rays and UV for these events show similarities which could suggest a fairly simple interpretation on the surface. Further detail reveals evidence for a more complex X-ray structure. The image reconstructions depict three well-resolved sources on the left ribbon during the maximum activity

Figure 3.25 Sample sequence of TRACE images from 07:02:40-07:04:10 with 25-100keV X-ray contours from the RHESSI image reconstructions.

(07:02:40). from the X-ray and UV observations alone it is impossible to definitively determine the magnetic connectivities and their implications for this events without necessary magnetic field extrapolations.

In this chapter, we have reports both timing correlation results and spatial development studies for two flares within our study. Though both flares presented verified the overall time correlations previously reported (Cheng et al, ,1988), the events showed significant differences in both temporal and spatial development on an individual source level. These developmental differences from two flares in the same active region raises numerous questions with present flare interpretations. In

the next chapter, we put forward an discussion of the implications of these events and address several possible factors to explain the varied behavior in addition to the overall correlation.

Chapter 4

Discussion and Interpretation

4.1 Observation Summary

The observations detailed in the previous chapter present a number of interesting facts illustrating the complexity of the magnetic field involved in solar flare energy release. The 16 July 2002 event proved to be considerably more complicated with regard to both the temporal and spatial development than its small flare classification would indicate. An initial key result in the description of this flare was the verification of the overall timing correlation between the hard X-ray and UV emission. The strong correlation between the time profiles of the UV and hard X-ray emissions suggests that these different emissions must result from the same energy release process, generally believed to be magnetic reconnection in the corona.

The separation of the UV emission into individual sources provides a more detailed examination of the various components contributing to the overall temporal behavior. Assuming each hard X-ray burst to be associated with particle production enhancements from the energy release site, the spatial distribution of the coincident and correlated UV emission present a unique diagnostic for the role of magnetic topology in particle production and transport. For the 16 July 2002 event, the TRACE observations detail a two-ribbon structure with the bulk of the UV brightening associated with the hard X-ray bursts lying within the upper, or northern ribbon. This

ribbon brightens in four spatially separated sources which appear in sequence as a progression along the ribbon over time.

The hard X-ray imaging data showed a much simpler picture with the hard X-ray footpoints confined to a small area situated adjacent to the lower, or southern UV ribbon. The strong temporal correlation between the UV sources in the northern ribbon and the hard X-ray sources (Separated by 50-70 arcseconds or 36,000-50,000 km) in the southern ribbon suggest a more complicated overall picture of solar flares than the single loop models of earlier work. Models such as the partial precipitation model (Kane, Donnelly, and Frost, 1979) assumed a single loop structure in which spatial separation of the HXR and UV emission was only possible in term of atmospheric height of emission. In our case the clear spatial separation on the solar disk point to a larger role of the 3D topology of the active region magnetic field. Such magnetic complexity is a key component in coronal mass ejections, the largest of which are often accompanied by large flares (Antiochos, 1998). These models involve multipolar magnetic configurations to provide the initial conditions for eruptions to occur.

It should be noted that there is evidence for a magnetic connection between the correlated HXR and northern ribbon UV sources in the 16 July 2002 event. The lower energy RHESSI images (6-12 and 12-25 keV) provide evidence for a hot thermal structure connecting the two (shown in Figure 4.1). This longer thermal loop has an evident footpoint which occurs near the left end of the lower UV ribbon coincident

Figure 4.1 Soft X-ray overlays both during the initial buildup of the 16 July 2002 flare as well as during the X-ray peak with the base images provided by TRACE. The white contours are the observations of 12-25 keV while the yellow contours show the 6-12keV emission.

with the 25-100keV X-rays. The other "conjugate" footpoint of the loop completes the proposed connection. From the observations in TRACE and RHESSI, we have determined an observational picture of this flare involving two known emission loops containing varying types of emission together with a more complex extended ribbon morphology. The emission in both loop structures must be governed by the same energy release process in order to maintain the temporal relationships observed. How this energy release process relates to the magnetic topology is a crucial question in

understanding the timing signature we observe.

An overall interpretation of the behavior of this event requires a simultaneous explanation of both the multiple ribbon structures and the temporal relationships. The hard X-ray emission of at 25-100 keV (non-thermal) and 12-25 keV (thermal) show evidence for a scenario in which the reconnection is driven by the interaction of two magnetic bipolar loops while the correlated UV ribbon emission strongly suggests that this is a part of a larger 3D topology. The following sections describe these implied scenarios in greater detail.

4.2 Loop-Loop Interaction

As the name implies, the loop-loop interaction scenario is a consequence of the interaction of two magnetic loop structures. This can occur due to the emergence of a new magnetic bipole from below the photosphere to interact with the existing coronal magnetic field or as a result of large-scale photospheric motions drawing the loop structures together. This occurs due to the fact that the field lines are tied to the photosphere and consequently move with it. If the loop fields are oriented with oppositely directed fields approaching each other, reconnection can occur to change the field configuration, releasing energy in the process (Nishio et al, 1997).

The imaging observations discussed in Chapter 3 seem to suggest that reconnection due to the interactions of the two loops is occurring. The hard X-ray observations at 25-100 keV clearly show two closely separated sources in the southern ribbon of

Figure 4.2 Sketch interpretation from Nishio et al. (1997) depicting the loop-loop interaction scenario as seen in their study with HXR and microwave emission

the 16 July 2002 event. Such high-energy emission is the result of the interaction of reconnection-accelerated particles with the ambient ions in the high-density chromosphere. As a result the X-ray sources observed represent the footpoints of a newly energized magnetic loop. The lower energy thermal X-rays (12-25 keV) indicate a pre-existing loop connecting the two UV ribbons (See Figure 4.1) with one footpoint near the higher energy sources. This description points to a scenario similar to that depicted in Figure 4.2. This scenario is consistent with the temporal correlation results which indicate that the brightest sources in the northern UV ribbon are correlated

with the hard X-ray emission along with a strong UV source in the southern ribbon near the hard X-ray structures. The correlation between the UV ribbons indicate a direct connection between the ribbon directly leading to a loop-loop interaction picture.

While this picture can provide a suitable explanation for the bulk of the hard X-ray sources and the emission from the brighter UV sources. It is unable to explain all of the flare-associated ribbon structures or their temporal development. The significant production of hard X-rays strongly support a scenario like the one described here. However, the loop-loop scenario must be a piece of a larger topological picture which distributes the energy from the reconnection site within the interaction region of the loop structures throughout the whole system.

4.3 Reconnection Along Separatrix Surfaces

A complete understanding of solar flare behavior must not only be able to explain the causes and locations of the magnetic energy release but must also be able to address the link between this release and the flare emission signatures in the chromosphere. Recent studies on the importance of separators and separatrix surfaces in solar flares have further developed the importance of 3D magnetic topology in the energy release and response in flares (Longcope, 1996; Démoulin et al, 1993). Separatrix surfaces divide the active region magnetic volume into distinct flux systems. These surfaces are defined by locations of discontinuities in the mapping of magnetic field

lines using equation 4.1 (Longcope, 1996):

$$\frac{dr(s)}{ds} = \frac{B(r(s))}{|B(r(s))|} \quad (4.1)$$

where r is a given field line and s is the position along the line. When two flux systems interact, the separatrices intersect along a single field above the chromosphere, known as a separator. Due to its position and the increased likelihood of magnetic connections between the interacting boundaries make this separator field line a prime location for reconnection to occur (Démoulin et al, 1993).

Figure 4.3 Map of the positions of hard X-ray emission sources relative to calculated separatrix surface boundaries for a white light flare from 25 Aug 2001

The separatrix surfaces can be mapped from chromospheric observations. Kernels of emission in $H\alpha$ and $O\,V$ have been shown to occur near the intersection of the separatrix with the chromosphere (Démoulin et al, 1993; Longcope, 1996). Metcalf et al. (2003) showed hard X-ray emission sources to also appear near the separatrix

boundary at the chromosphere (See Figure 4.3). This relation of separatrices to the flare response provides more evidence for flux system interaction by the inference of separatrix boundaries near our ribbons of emission.

Our observation of the 16 July 2002 event provides significant evidence for a three-dimensional reconnection picture of two separatrices varying over time and in all three spatial dimensions but is primarily driven by reconnection at a separator in the vicinity of the high energy hard X-ray sources. The primary justification results from the observed brightenings in the upper ribbon of UV emission brightening as a progression down the ribbon. We see this ribbon's emission develop as four separate brightenings over the duration of the flare. UV emission results from the energy deposition by injected electrons (Kane, Donnelly, and Frost, 1979). Therefore, the individual spatially separated brightenings must result from the injection of newly accelerated electrons at the reconnection site. The spatial progression over time of the UV emission in the upper ribbon suggests a progression of the connectivity to the particle injection site as the flare progresses. The lowest energy hard X-ray emission, 6-12 keV, shows the existence of substantial heating within a large volume encompassing both UV ribbons suggesting once again that the magnetic field connects all the emission sites to the initial energy release at the separator. The observed progression would result naturally from the growth of the newly-emerged flux system, discussed in Section 4.2 generating the dynamical evolution of the separator and likewise the connectivities

within the magnetic volume, i.e. the progression of the reconnection along the separator defined above. The more dynamic behavior exhibited by the UV source of the upper ribbon is consistent with the scenario described since the reconnection is expected to be closer to the southern ribbon near the hard X-ray emission.

A detailed knowledge of the coronal magnetic field in this flaring region is required to confirm the hypothesis adopted to explain our observations. This requires acquiring the photospheric vector magnetic field data and performing detailed extrapolations to define the separatrix topology (see Metcalf et al, 2003).

4.4 Particle Production from the Reconnection Site and the Implications of Varied Emission

The mere existence of an interacting magnetic structure does not specifically address the types of emission visible from each ribbon structure, i.e. why no high-energy hard X-rays from the northern UV ribbon of the 16 July 2002 event. The types and locations of emission visible are governed predominantly by the magnetic field configuration and the ambient plasma conditions in the chromosphere. In the case of the 16 July 2002 event, we see two predominant X-ray loops. One loop was evident from the appearance of the footpoints of a tightly confined ribbon of 25-100 keV hard X-rays. This hard X-ray emission at the stated energies is dominated by non-thermal emission from thick-target bremsstrahlung at chromospheric depths (Alexander and Metcalf, 1997) resulting from an injected beam of non thermal electrons produced at the re-

connection site. Electrons producing the hard X-ray emission are transported down the magnetic field within the HXR loop to collisionally interact in the high-density chromosphere. In the case where the field has a steep magnetic gradient, the particles can mirror due to the increasing Lorentz force and 'bounce' from one side of the loop to the other. Only those electrons which directly precipitate to the chromosphere or are scattered into the chromosphere by collisions can produce chromospheric hard X-ray emission. The chromospheric magnetic field is often of different strength at the respective endpoints resulting in asymmetries in hard X-ray emission (Alexander and Metcalf, 2002). Numerous models have described observations of HXR loops like this one through this magnetic trapping scenario which allows for both direct precipitation as well as additional precipitation due to pitch angle scattering effects (Kane, Donnelly, and Frost, 1978; Alexander, 1990; Alexander and Metcalf, 1997). Verification of this trapping scenario requires a knowledge of the coronal magnetic field distribution to address the effects of the smaller magnetic geometry figures such as these tightly constrained X-ray loops. A detailed study of the magnetic field is required to further address this issue.

In contrast the second loop is depicted through the signatures of softer X-ray emission (6-12 keV and 12-25 keV) which is predominantly governed by thermal emission rather than the non-thermal component in the HXR loops. This does not preclude the electron injection from being non-thermal. In fact given the temporal profile already

addressed it stands to reason the non-thermal electrons from the injection beam also serve as a source population of this thermal ribbon as well. The differences arise in the process by which energy is transported to the chromospheric levels. The non-thermal electrons, when confined by the magnetic field to this longer second loop, propagate along the magnetic field before depositing their energy into the chromosphere. While the emission of hard X-rays can be modeled by the trap-plus-precipitation model, the electrons propagating in the longer loop produce both lower energy hard X-rays and UV emission. The specific mechanism for the UV emission production is not yet understood. One potential mechanism would be particle transport in the thermal loop with particles of lower thermal energies being preferentially accelerated in the thermal loop. Further work will be done to address correlations between the UV and the thermal X-rays. Since both thermal and non-thermal emission is produced in this loop, it is necessary to include sources for both thermal and non-thermal emission. The X-ray emission shown in this loop is still believed to be a result of an injected non-thermal electron beam as in the previous X-ray emission scenarios. However, the UV emission is believed to result from bulk heating which is potentially the result of a thermal conduction front or other thermal source. This bulk heating energizes the ambient chromospheric particles to produce the UV ribbon emission seen. Further explanation of this scenario also requires magnetic field extrapolation to determine the specific energy deposition.

4.5 Active Region Temporal Progression

As was addressed during the flare selection process, we return to the fact that both flares presented here originated from the NOAA active region 10030 (hereafter AR0030). The events occur ~ 24 hours apart within AR0030. Figure 4.4 shows a differentially rotated image including as a background image the magnetogram data from SOHO/MDI at 06:24 UT with overlays of a sample TRACE image for both events (16 Jul 2002 event is in blue contours while the 17 Jul 2002 event is depicted in orange contours).

Figure 4.4 MDI magnetogram image of AR0030 containing overlays of TRACE images from the respective flares discussed.

The events occur at distinct spatial locations within AR0030 which are separated

by ~ 50 -80 arcseconds. Each set of UV ribbons exists as a connection to regions of opposite polarity of the magnetic field. The 17 July event occurs with one ribbon near the spatial location of the strongest positive field denoted by white emission in the magnetogram while the other ribbon is near a very strong negative polarity magnetic field. The 16 July event has a similar bipolar characteristic in a region of lesser magnetic field values from initial observation. This conclusion is consistent with the 17 July region producing the much larger flare event. We believe that the 17 July event observation could be described by a similar topological scenario. The multiple loops of both hard X-ray and UV emission lead to multiple separatrix scenario; however unlike the previous event the fluctuation of the hard X-ray emission between the multiple ribbons (See Figures 3.24 and 3.25) along with the stronger magnetic fields yield much greater complexity. Noting that these two events occur at such spatially distinct locations leads to a prospect for future analysis to address the evolution of this region in an attempt to understand what processes govern the development of flare production within the active region.

Chapter 5

Future Work

5.1 Magnetic Field Extrapolation

The coordinated observations of the 16 July 2002 flare provide crucial diagnostic information regarding the relationship of the parent active region's magnetic topology and the flare-related energy release. In order to address both the spatial distribution and temporal evolution of the UV and HXR emission, we developed a picture by which the flare energy release is governed by the interaction of two magnetic flux systems. Locally, we described this interaction through a loop-loop interaction scenario as described by Nishio et al. (1997) and then included the larger volume as part of a separator reconnection picture to address larger scale ribbon emission. However, without knowledge of the 3D coronal magnetic field our scenario for this flare is merely observation supported speculation. To confirm the topological picture suggested by our observations, we plan to employ force-free magnetic field extrapolations to calculate the the 3D topology from the observed surface field data.

Presently, coronal magnetic field observations are only available in very limited cases. The standard procedure employed in cases where no such data exist is to use the photospheric field value as a lower boundary condition and extrapolate to the corona assuming a force-free condition:

$$\nabla \times B = \alpha B \tag{5.1}$$

where the factor α can take three forms:

- For $\alpha = 0$ the magnetic field is called a *potential* (current-free) field.
- For a constant non-zero α , we have a *linear* force-free field.
- If α is a function of position, we have spatially distributed current and a *non-linear* force free field.
- Please note that α is constant along any given field line.

The extrapolations for each of the flares in our list will be performed by Dr. Thomas Metcalf, a collaborator at Lockheed Martin Solar and Astrophysical Laboratory. This collaboration will allow the verification of the 3D topological scenario and continue to develop our understanding of the UV/HXR relationships. The extrapolations will be able to clarify the 3D magnetic evolution by providing the distribution of separators and separatrix surfaces for each event.

Beyond the global magnetic developments and structure, the field extrapolations can be applied to localized magnetic structures within the areas of emission to obtain a further understanding of local magnetic geometry effects on the particles accelerated and the emission produced. For example, the production of hard X-rays in a loop structure is believed to develop from a magnetic trap plus precipitation model (McClements, 1990; Alexander, 1990; McClements and Alexander, 2005) where the electrons from the initial energy injection are accelerated down the magnetic field and

either directly precipitate in the chromosphere or mirror in a converging magnetic field depending solely on their pitch angles relative to the magnetic field. The particles which mirror are considered trapped in the corona as they are confined between mirror points on either side of the loop until pitch angle scattering, e.g. via collisions, allows the electron to precipitate and deposit its energy in the chromosphere. The magnetic field gradient which creates the trap is dependent on the field strength at each chromospheric location relative to the coronal field strength at the particle injection site. The maximum pitch angle permitted for direct precipitation, the loss-cone angle, is defined by:

$$\sin\theta_c = \left(\frac{B_{inj}}{B_{chrom}} \right)^{1/2} \quad (5.2)$$

where B_{inj} is the injection site field strength and B_{chrom} is the chromospheric footpoint field strength. Electrons with pitch angles less than θ_c will reach the chromosphere and deposit energy.

By employing the force-free magnetic field extrapolations, discussed above, we will be able to determine the magnetic geometry of the emitting sources from which we can infer locations of strong chromospheric energy deposition comparing them to the locations of the observed emission.

5.2 UV lag calculations

In their study of temporal relationships between UV and hard X-ray emission, Cheng et al. (1988) found evidence for a time lag between the UV emission (OV at

1371Å and a UV continuum measurement peaked at $\sim 1388\text{\AA}$) and the hard X-ray bursts. They report a lag values in the range 0.3-0.7 seconds with the OV emission lagging the hard X-ray emission (25-225keV). While a number of the burst structures in our analysis show strong correlation prior to the addition of a lag, we wish to investigate whether these correlations can be appreciably improved by the addition of such a lag.

In our study of the individual bursts within the UV and hard X-ray time profile of the 16 July 2002 event, we have conducted lag analysis for 3 time periods: (a) the full time range of the flare (06:38:00-06:43:00), (b) the interval 06:39:30-06:40:10 which includes the first larger scale burst of the hard X-ray profile, and (c) the interval 06:40:10-06:40:40 containing the second large-scale burst. Figure 5.1 shows the results of our correlation vs time lag comparisons for cases (a) and (b). For case (a), we see a moderate increase in correlation coefficient as the UV lag approaches a value of 1.6 seconds where the Spearman rank correlation reaches a maximum of 0.924 compared with the correlation of 0.910 with no delay. The lag of 1.6 seconds in this observations is longer than that reported by Cheng et al (1988). A possible explanation for this discrepancy lies in the fact that Cheng et al. used OV lines and a UV continuum measure at 1388Å while the present study uses a UV continuum peaked at 1600Å . This presents intriguing questions as to the dependance of lags on wavelength observed.

Figure 5.1 Plots of correlation coefficient vs. UV lag for the complete time range (left) as well as for the initial burst of HXR emission (right).

When the analysis is confined to the time range containing the initial HXR burst (case b, Figure 5.1), we find similar behavior to that of the full time range. The maximum correlation coefficient within the range of ± 3 seconds of lag is found for a lag value of 1.3 seconds. The recorded value of this maximum is 0.907 compared with the initial value of the 0.848 with no delay. The larger improvement for the shorter time frame compared to the overall time profile is as expected because the correlation of the full-time range is weighted by long-range temporal correlations.

We address separately the second hard X-ray burst in the 16 July 2002 flare

(06:40:10-06:40:40) that displayed no significant correlation between the hard X-ray and UV emission. Introducing a lag for this burst, We find a large delay of approximately 6.5 seconds is required for the correlation to reach its maximum value of 0.619 (Figure 5.2). The lag reported for this burst is markedly longer than both the results

Figure 5.2 Results of lag studies for the second burst in the 16 July 2002 flare from 06:40:10 to 06:40:40. We note the maximum correlation of 0.619 after a time lag of 6.5 seconds

from the first burst and the results previously reported by Cheng et al. (1988).

We do not yet understand the reason for the poor correlation nor for the larger delay necessary for significant correlation. As a future extension to this thesis, we will apply this lag analysis to the remaining flares in our sample to determine if

these delays are consistently observed and whether we can develop a picture of the relationship between the UV and HXR response to the initial flare energy release.

5.3 Active Region Development

The two events detailed in the results of this thesis were flares that occurred in the same solar active region (NOAA active region 10030). These flares take place in spatially separated areas of the active region, with different magnetic field configuration. A study of this active region as it progresses between the times of flare activity will allow us to address the role played by changes in the magnetic complexity and evolution in driving the flare energy release. For example a study of the MDI magnetogram observations preceding a flare event could provide evidence of emerging flux or flux cancellation. The former arises from the emergence of new magnetic bipoles from below the photosphere while flux cancellation results from similar bipoles being submerged or from the reconnection and flare initiation. Both mechanisms significantly alter the coronal magnetic field configuration inducing energy release which could drive the temporal and spatial correlations observed.

We plan to use SOHO/MDI magnetogram observations both leading up to and following the flare events in our study. Comparisons of these observations for all of our events will permit us to assess the role of this significant magnetic evolution with the active regions in flare initiation.

Appendix A

A.1 Summary of Remaining Flares

This appendix provides a tabulated summary of the remaining flares in our study.

Table A.1 includes the dates, times and flare classification while Table A.2 contains the active regions, the number of UV sources, the overall correlation coefficient and a UV spatial description of the flares.

Flare Number	Date	Time Range (UT)	X-Ray Class
2070405	4 July 2002	07:28-07:35	M 1.1
2070703	7 July 2002	03:57-04:05	C 3.5
2071811	18 July 2002	22:56-23:04	C 8.2
4011911	19 January 2004	12:30-12:38	M 1.1
4111002	10 November 2004	02:03-02:11	X 2.5
4122801	28 December 2004	00:07-00:13	C 7.2

Table A.1 Reprint of the data from Table 2.1 for the flares in this study not detailed in Chapter 3

Flare	AR	UV Sources	Correl. Coeff.	Description
2070405	10017	6	0.844	C-shaped
2070703	10021	8	0.731	Multiple ribbon
2071811	10030	6	0.623	Single ribbon
4011911	10540	6	0.863	C-shaped
4111002	10696	11	0.733	Multi-ribbon
4122801	10713	2	0.691	C-shaped

Table A.2 Active regions, number of UV sources, whole flare UV/HXR temporal correlations and UV spatial descriptions for the remaining flares in our study.

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