Simultaneous Observations of the Solar Limb with TRACE and SUMER

by

Evan Tingle

Class of 2008

A thesis submitted to the faculty of Wesleyan University in partial fulfillment of the requirements for the Degree of Bachelor of Arts with Departmental Honors in Astronomy

Middletown, Connecticut

April, 2008
Acknowledgments

I would first like to thank my advisors, Professor Jay Pasachoff of Williams College and Professor Bill Herbst of Wesleyan University. Professor Pasachoff has given me an incredible opportunity to work with amazing data sets and amazing scientists and has instilled a passion for a balance between scientific research and public outreach that has shaped not only my last year as an undergraduate, but also my future. Professor Bill Herbst has helped me immensely not only though the thesis advising process, but throughout my undergraduate career and I look forward to working with him next year. Ingolf Dammasch has been of immeasurable help concerning every possible aspect of the SUMER data. Alphonse Sterling has contributed his knowledge and expertise to the project. Also, my family deserves a great deal of credit. My parents have encouraged my studies in whatever shape they might take and have given me the opportunity to attend such an amazing place as Wesleyan. Also, I hope that this project might be the starting point in a series of contributions and accomplishments performed by the Tingle siblings. I would like to thank my friends at Wesleyan, who have truly shown me the best of what great students at a great school like Wesleyan can do.

Thanks to David Butts and Joseph Gangestad who helped with the 2004 SST data and thanks to all the students, faculty, and alumni of Williams College who made my summer in Williamstown an incredible experience.

Obtaining the chromospheric data was supported in part by NASA grant NNG04GK44G from the Solar Terrestrial Program and the current reduction work is supported in part by NASA grant NNM07AA01G from NASA’s Marshall Space Flight Center.
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Chapter 1

Introduction

The original intent of this project was to study spicules in the solar chromosphere, but has since evolved to also encompass coronal loops after the strongest signal measured in our data from the SUMER instrument on the NASA and European Space Agency’s (ESA) Solar and Heliospheric Observatory (SoHO) happened to correspond to a bright loop structure. The following presents a background and history of the study of solar phenomena relevant to this project along with a discussion of the importance of such studies.

1.1 The Solar Atmosphere

The solar atmosphere is an intricate and complicated interplay of powerful magnetic forces, violent dynamics, and temperature extremes. The sun does not have a solid surface because the solar mass is composed of 70% hydrogen and 28% helium heated anywhere from 4,500 K on the surface to 16 MK (16 MegaKelvin or 16,000,000 Kelvin) deep within the core where fusion is taking place. Though
not solid, the first layer of the solar atmosphere and the visual surface of the sun, or photosphere, coming from the Greek word \textit{photos} for light, exists around 4,500 K–6,000 K. The photosphere is overwhelmingly brighter than the higher layers of the solar atmosphere, but is strangely cooler than those atmospheric layers as well, giving rise to what is known as the coronal heating problem, to be discussed later. As an observer looks deeper into the photosphere, the material very quickly becomes more opaque, giving the photospheric disk a sharp edge.

The next layer of the solar atmosphere, the chromosphere, coming from the Greek word \textit{chromos} for color, is named so because of its reddish color, corresponding to its dominant H\textalpha emission (6,562.8 Å). Also, even though the chromosphere is generally drowned out because of the intense radiance of the photosphere, it is visible through a narrow-band H\textalpha filter, or briefly during a solar eclipse as a reddish ring around the silhouetted moon (See Figure 1.1). This layer has been measured from 4,500 K–20,000 K and is of particular importance regarding solar phenomena, as it is entirely composed of spicules.

The next layer of the solar atmosphere, the transition region, forms the boundary between the lower temperatures of the chromosphere and the extreme temperatures of the corona. The transition region marks the delineation between the cooler chromosphere and the extremely hot corona. Though generally thought of as layers, since the chromosphere is made of spiky structures, the transition region must exist on the sides of those structures and the corona’s lowest levels must be between the spicules. Within the few hundred kilometers of the transition region, the temperature of solar material increases from about 10,000 K to 1 MK. This abrupt heating is the source of much debate within the field of solar atmospheric
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studies and is still being explored today.

![Eclipse image showing the chromosphere. Notice the red ring produced by the dominant Hα emission. Image taken by Martin Ratcliffe, as part of the Williams College Eclipse Expedition to Kastellorizo, Greece, March 29, 2006.](image)

**Figure 1.1:** Eclipse image showing the chromosphere. Notice the red ring produced by the dominant Hα emission. Image taken by Martin Ratcliffe, as part of the Williams College Eclipse Expedition to Kastellorizo, Greece, March 29, 2006.

The highest and most extensive region of the solar atmosphere, the corona, which is Latin for crown, exists at a temperature of about 1 MK–3 MK. Because of these extremely high temperatures, coronal observations are best made at high-energy wavelengths, generally in the realm of extreme ultraviolet or x-ray bands. Although the corona has the highest temperatures of the solar atmosphere, it is very dim, about one millionth the brightness of the photosphere, and is overwhelmed by the bright photosphere, like the chromosphere. But filters that allow only the highest-energy wavelengths, such as extreme ultraviolet and x-ray, let observers see the corona while blocking the intense radiance from the lower energy emissions of the photosphere. Also, as in the case of the chromosphere, the corona is visible briefly during a solar eclipse as an extended halo around
the silhouette of the moon (See Figure 1.2). But solar eclipses occur infrequently, about once every 375 years, changing slightly with latitude. So astronomers either travel to the site of the eclipse, as with the Williams College Eclipse Expeditions, or make their own artificial eclipses with what is known as a coronagraph. A coronagraph blocks the emission from the solar disk and the lower layers of the solar atmosphere, making sure that the glare from the brighter regions of the atmosphere is not mistakenly imaged. Coronagraph observations from the Large Angle Spectroscopic Coronagraph, or LASCO, on the SoHO spacecraft, and now with the STEREO spacecraft, have observed the corona as extending as far out as $2.23 \times 10^{10}$ km from the photosphere, or about 1/6 of the distance from the Earth to the Sun, known as an Astronomical Unit, or A.U.

Figure 1.2: Eclipse image showing the corona. Notice how far the corona extends from the solar disk compared to the chromosphere (Figure 1.1).
1.2 Histories and Descriptions of Notable Solar Features

1.2.1 Spicules

The study of spicules, or jets of solar material that originate in the solar photosphere, began in the 1870’s with Father Angelo Secchi’s observations that described the phenomena as “small and irregularly arranged flames” with “the appearance of a burning field.” Research on these objects did not resume until the 1940’s, when Walter Roberts of the Harvard College Observatory’s field station in Climax, Colorado, recorded the first quantitative observations of spicules, including heights, velocities, and lifetimes. Ground-based observations of the solar surface have long been used although the recent availability of adaptive optics and advanced post-processing techniques, such as Multi-Object Multi-Frame Blind Deconvolution used with observations from the Swedish 1-meter Solar Telescope (SST), have mitigated much of the obscuring effect of seeing. Spicules appear more clearly at lower wavelengths while higher wavelengths, as in 171 Å observations from the TRACE solar observatory, which show the corona in highly ionized iron (Fe IX/X) emission at temperatures of 0.16 MK–2 MK, reveal spicules as dark absorption features against the hotter coronal background emission. Spicules seen in absorption are harder to track and measure than those observed at lower wavelengths. As they are known today, spicules extend from 2,000 to about 10,000 kilometers above the solar limb, populating the chromosphere. Observations of spicules usually reveal lifetimes of about 5 to 10 minutes, although measurements of 3 to 15 minutes have been recorded. Spicules propagate from the photosphere
at every angle of inclination and combined transverse and radial motions reveal an average velocity of 20 km s$^{-1}$. Discussion remains whether some component of spicule motions can be attributed to ballistic motions or if all of the material follows complicated magnetic field lines.

1.2.2 Coronal Loops

Since large coronal loop features can be seen most effectively in shorter wavelengths, such as the extreme ultraviolet and x-ray bands, where the permitted lines from the highly ionized coronal ions lie, missions to observe these phenomena needed to travel outside of the Earth’s atmosphere that protects life from these harmful rays. Sounding rockets, such as the American Aerobee and the British Skylark, provided some of the first high-energy observations of the sun, but these observations were short lived as the rockets never fully reached orbital speeds or heights. The launch of the Orbiting Solar Observatories (OSOs) from 1962–1975 was intended to gather information about an entire 11-year solar cycle and marked the beginning of reliable data from the ultraviolet to the gamma-ray bands of solar surface phenomena. Coronal loops have been measured at myriad sizes, routinely ranging in length from a few dozen Mm to almost a million kilometers long. Because of the intense heating that occurs in these loops, they are often observed at very energetic wavelengths, such as the extreme ultraviolet and the x-ray band. As material is pulled from the relatively cool chromosphere, it is quickly heated to temperatures of multiple MK as it rises high into the solar atmosphere. This aspect of coronal-loop heating makes the structures very popular for study to learn more about the coronal heating problem. Although the
solar surface is covered with magnetic structures and field lines, a magnetic loop is known as a coronal loop only once it is filled with plasma. These coronal loops and other energetic and dynamic phenomena occur primarily in regions known as active regions, which have strong magnetic fields, but they can also be observed in quiet-sun regions. In active regions, large magnetic structures such as loops and flux tubes extend high above the photosphere and intense x-ray brightening on several orders of magnitude is observed.

1.2.3 Footpoints

When a coronal loop emerges and reconnects with the solar surface, it does so through bright regions known as the footpoints. Before the loop ever forms, these footpoints have already been brighter than the area around them because of the increased magnetic activity within the solar surface, creating the bright regions on the chromosphere known as plage. As the coronal loop forms, material from the chromosphere is pulled up one leg of the loop and travels along a strong magnetic field line to the other footpoint. One can imagine that a large magnet is below the solar surface, and that the material is merely following the magnetic field from one pole to another. These footpoints do not necessarily need to be one isolated region, as large extended coronal loops have exhibited extended footpoints surrounded by the associated spicules and other phenomena.

1.2.4 Moss

Another solar feature related to active regions of the sun resembles a small “spongy” mass, giving it the appropriate title of moss. In 1999, Berger et al. found that
moss generally occurs in strong plage regions and seem to be associated with the footpoint regions of coronal loops. They are usually found to be associated with coronal loops of temperatures 3 MK–5 MK and have temperatures themselves of 0.6 MK–1.6 MK. Moss also has been measured to have a higher density than the actual coronal loops and is best seen in the extreme ultraviolet emissions, though some patterns of moss have been observed in 1,600 Å continuum emission on TRACE images.

1.2.5 Coronal Holes

Highs and lows in the energy output of the sun are known as solar maximums and solar minimums and occur in 11-year cycles known as the solar cycle. At the time of the writing of this thesis, the sun was at a solar minimum with no sunspots being observed for days. Although the measurements for this project were taken in 2004 while the sun was still declining into a solar minimum, many more sunspots and energetic events were observed than during the early months of 2008. All of the regions observed for this project lie either bordering or within a relatively darker region on the surface of the sun, called a coronal hole. During periods of solar maximum, the coronal holes can be found at all latitudes on the solar surface, but during the solar minimum, only the coronal holes at the polar regions of the sun remain, although SoHO has sometimes observed them at differing latitudes as well. Here, lower temperatures and pressures exist compared to the surrounding quiet sun regions. Young et al. claim that the coronal-hole region can be defined as “no Si XII emission, and where the Mg IX line has a signal of 50-100 erg cm$^{-2}$ s$^{-1}$ sr$^{-1}$.” In addition, the coronal hole has open magnetic-field lines that
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extend into space, allowing charged particles to escape at very high velocities; this phenomenon is called the solar wind. The Ulysses spacecraft has measured the solar wind as variable with latitude, with speeds of about 800 km s\(^{-1}\) at higher latitudes, while speeds of about 400 km s\(^{-1}\) have been measured closer to the solar equator. Without Earth’s protective magnetosphere, this solar wind would make life on our planet difficult or impossible. The outflow of energetic particles occurs on all stars and is a factor that could dramatically affect the possibility and types of life on other planets. These solar features, visible in Figure 1.3, will help decide what regions of the sun to observe to find a certain type of solar phenomenon.

Figure 1.3: Full solar disk observed with the Extreme ultraviolet Imaging Telescope (EIT) instrument aboard SoHO. This image was taken in 171 Å on May 24, 2004, at 7:00:14 UTC, about an hour before the study s309701 started. The black lines indicate the position and vertical area observed with this project’s SUMER studies.
1.2.6 Space Weather

The importance of the study of spicules and other solar phenomena lies in the counterintuitive effect of the coronal-heating problem. When measuring an object that is radiating energy, one expects the intensity to drop as the observations move further from the object. When measuring intensity from the sun, however, the observations show that the surface is 6,000 K, while the upper reaches of the atmosphere, such as the corona, are measured in the millions of Kelvin. Studies of spicule dynamics hope to recognize the coronal heating as a product of the magnetic forces and magnetohydrodynamic waves, which are also partially responsible for the motions of the spicules.

More broadly, increased understanding of the nature of solar activity and outbursts constitute a new area of study known as space weather. Extreme bursts of energetic particles from the sun, such as coronal mass ejections and solar flares, have been known to temporarily knock out communication networks or disable them completely. One incident, recorded in 1859, was strong enough to short out telegraph lines, starting fires and generating aurorae borealis, a solar-related phenomenon normally seen only around the polar regions, as far as Hawaii and Rome. A massive solar flare was eventually identified as the culprit with historical observations of collections of sunspots helping researchers to recognize what caused the incident. More recent flares and coronal mass ejections have caused millions of dollars in damages and the malfunction of communication systems but have not been remotely as powerful as the flare experienced in 1859. More pertinent to recent decisions to send humans back to the moon and on to Mars, these events could also endanger astronauts in orbit if they are unshielded from
1. Introduction

such energetic particles. Thankfully, no astronauts have been affected by such an incident, though extending the duration of manned space missions increases the risk. As global navigation becomes increasingly reliant on GPS (Global Positioning System) satellites, and as global communications becomes more integral to society, the ability to predict and alert the appropriate agencies about possible disruptive solar activity becomes more important than ever. Fortunately, with more sensitive solar observatories in space such as SoHO coupled with a greater understanding of the science involved in solar weather, forecasts and warnings can be issued days in advance before the energetic particles reach Earth, allowing agencies to make the proper preparations as with a large meteorological storm.

1.3 Instrumentation

1.3.1 SoHO (Solar and Heliospheric Observatory)

The SoHO satellite holds twelve different instruments used to study many aspects of the sun including helioseismology, the nature of the solar atmosphere, and the origin of the solar wind. The satellite, a joint effort between the European Space Agency (ESA) and NASA, was launched on December 2, 1995, from Cape Canaveral on an Atlas II-AS rocket and is locked in a halo orbit around the first Lagrangian point about 1.5 million kilometers from Earth. One of the accomplishments of the observatory is its ability to give solar weather forecasts for powerful solar eruptions heading towards Earth. Although the mission was originally planned to last two years, because of its resounding successes, the mission was extended until 2003, and again until March 2007 with the intention of
monitoring an entire solar cycle of 11 years. Most recently the project has been extended to December 2009 to help gather data simultaneously with the latest solar observatories, Hinode and STEREO.

Unfortunately, in 1998, during a gyroscope recalibration, the roll rate of a gyroscope was mistakenly left in the high-gain mode, effectively telling the scientists that the roll rate was 20 times greater than it actually was. The satellite then entered Emergency Sun Reacquisition (ESR) mode, an automatic response to a satellite malfunction. This mistake occurred multiple times before a gyroscopic cross-coupling caused the ESR controller to lose stability, at which point SoHO began spinning out of control and stopped responding to ground control. Almost a month elapsed before the SoHO team was able to find the spacecraft and measure its position and rotation with Arecibo and the 70-meter dish from NASA’s Deep Space Network. Among other problems, the hydrazine fuel tanks and lines needed to be thawed, the batteries recharged, and a new roll correction system implemented. Though the recovery process itself was an impressive feat of engineering and problem solving, another two months would pass before the satellite was optimally functioning. Today, SoHO is working almost as well as before the malfunction, with the exception of the loss of the LASCO C1 coronagraph.

Because the SoHO mission, which is scheduled to conclude in 2009 after almost 13 years of service, was originally designed for a two year mission, it is natural that parts of the satellite would start to deteriorate over time. Evidence for this deterioration is evident on Detector A of the SUMER instrument and other detectors aboard the SoHO spacecraft as several errant streaks in the horizontal direction that have not been removed by the reduction process. Exposure to
the powerful radiation of the solar wind is believed to be the main factor in the detector fault though further discussion is included later in the Problems section.

1.3.2 SUMER (Solar Ultraviolet Measurements of Emitted Radiation)

One of the main purposes of this project was to measure spicule dynamics accurately and to observe their evolution. Therefore, this project primarily used the SUMER instrument aboard SoHO because of its ability to measure very accurate velocities within the solar atmosphere down to less than 2 km s$^{-1}$. The SUMER instrument has two detectors with 1,024 spectral pixels and 360 spatial pixels each. This project used Detector A, which measures 780-1,610 Å in first order and 390-805 Å in second order and allowed observations of multiple emission lines simultaneously. Our data corresponded to three different wavelengths plus the continuum, each inhabiting a certain region of the solar atmosphere exhibited in the table below. With these observations of different layers and different temperatures, it was the intention of the project to map solar material propagating through different heights in the solar atmosphere in the form of spicules or as observed and discussed later in the Results section, coronal loops.

<table>
<thead>
<tr>
<th>Ne VIII</th>
<th>770.4 Å</th>
<th>630,000 K</th>
<th>Bottom of Corona</th>
</tr>
</thead>
<tbody>
<tr>
<td>C IV</td>
<td>1,548.2 Å</td>
<td>100,000 K</td>
<td>Transition Region</td>
</tr>
<tr>
<td>Si II</td>
<td>1,533.4 Å</td>
<td>14,000 K</td>
<td>Chromosphere</td>
</tr>
<tr>
<td>Photospheric Cont.</td>
<td>1,549 Å, various λ</td>
<td>6,000 K</td>
<td>Photosphere</td>
</tr>
</tbody>
</table>
Although several different slits are available, our project used the 1 pixel x 300 pixel spatial slit that gave a small but dedicated observation in the x-direction with an extended field of view above and below the solar limb. Our particular observations took place from May 24-27, in 2004, where SUMER took two scans daily of the northwest and southwest solar limb, corresponding to simultaneous observations by TRACE and SST. For each of these four days, the first observation that SUMER performed was of the northwest limb of the sun and lasted from the beginning of the first observation to the end of the last, or 1:28:32. For the first approximately 19 minutes of each scan, the focus of SUMER moved 10′′ eastward, 20′′ westward, then 10′′ eastward back to its initial x-coordinate of 265′′. The focus was then stationary for the remaining approximately 69 minutes of each study. This east-west motion, known as rastering, can be observed as the slight dip towards the left side of each image in Figure 1.4. Ultimately, data during this raster period was excluded when finding averages and standard deviations of y-coordinates and is discussed in further detail later in the section Problems.

With each wavelength, programs provided by Ingolf Dammasch produced four different images of the same scan: continuum radiation, line intensity, line width, and line shift. The continuum radiation displays the surface of the photosphere as identified in the reduction process and is scaled in intensity. The line intensity shows the specific wavelength, also identified during the reduction process and scaled in intensity. Even with a relatively cooler wavelength such as Si II, the line intensity shows the peak emission higher in the atmosphere than the peak continuum. In the next image, line width is measured as the Full-Width Half-Maximum in angstroms of the measured wavelength’s Gaussian line profile. This picture lets
the user see the turbulent motion of the solar material at that wavelength with
the greater line widths displayed as brighter colors than the more passive regions.
Generally the greater line widths reside further from the limb where phenomena
such as spicules are more visible, but if a region contains a large flare or another
sort of solar activity, the interior of the solar disk might appear with a greater
velocity dispersion. The focus of the project lies with the information conveyed in
the final image of the line shifts with red and blue pixels that correspond to the
redshifts and blueshifts of the solar material. The more red or blue the individual
pixel, the more intense the redshifting or blueshifting of the material. This image
allows us to see the actual velocities of the target material by making use of the
Doppler effect based on the difference between the rest wavelength and measured
wavelength. As with the line widths, the higher line shifts are normally found fur-
ther from the limb rather than towards the interior of the solar disk. An example
of these images can be seen on the next page in Figure 1.4.
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Figure 1.4: A sample scan from SUMER of the southwest solar limb from study s309802, taken in Si II emission (1,533.4 Å). From left to right: continuum radiation, line intensity, line width, line shift. Notice the dip towards the left in each image that corresponds to the rastering at the beginning of the scan. After traveling 10″ westward, the scan moved 20″ eastward, creating the black peak seen after the initial dip. The raster then moved 10″ back westward where it stayed the rest of the scan. The plots are a time series with the spatial values as the y-coordinate and time as the x-coordinate.

1.3.3 SST (Swedish 1-Meter Solar Telescope)

As a complement to the relatively poor resolution of SUMER, the SST was chosen as a high-resolution imaging telescope, along with simultaneous observations from the TRACE spacecraft. This ground-based telescope located on La Palma in the Canary Islands was used in 2004 by Professor Jay Pasachoff along with Williams College students David Butts ’06 and Joseph Gangestad ’06, to take simultaneous images of the same regions observed with SUMER and TRACE in an attempt to add high-resolution and high-cadence observations to the data set. As a testament to the impressive qualities of this observatory, features have been measured with resolutions smaller than 0″.2 with SST at an extremely fast cadence of 30 Hz. This quick succession of high-quality images is incredibly useful for tracking the evolution and dynamics of solar surface phenomena, such as surface granulation.
and spicules. Unfortunately, SST data taken during the overlap period exhibited the limitations of ground-based observing as much of the data taken was of low quality due to poor earthly atmospheric conditions. Two datasets of simultaneous observations, SUMER and TRACE, were deemed adequate for the purposes of this project and the data from SST was excluded from analysis. Future observations of spicules and small-scale structure evolution would benefit to use the impressive capabilities of the SST.

At the time of the writing of this thesis, Will Jacobson of Williams College is simultaneously writing about more recent SST observations, from 2006, using the MOMFBD (Multi-Object Multi-Frame Blind Deconvolution) reduction technique. For this reduction technique, the SST takes three images at different foci, one slightly in front of the focus, one at the focus, and one slightly behind the focus. The MOMFBD technique then combines groups of these images with a pinhole alignment procedure to create one stunningly detailed image.

1.3.4 TRACE (Transition Region and Coronal Explorer)

While SUMER was able to measure detailed velocities, its low resolution and narrow field of view made it difficult to visualize the solar activity taking place and creating said velocities. The aim of this project was to measure velocities with the SUMER instrument and to co-align the times and positions of spicule candidates with the higher resolution images of TRACE as a way to visualize their lifetime and evolution. These observations were later made into movies to illustrate the passage of time and changing morphology of the solar phenomena.

TRACE was built to help answer the questions surrounding the evolution and
dynamics of magnetic structures, such as coronal loops, flux tubes, spicules, and various newly observed features, such as solar tornados, and their interaction with the extreme heating of the corona. Launched on April 2, 1998, from a Pegasus XL rocket, TRACE is now fixed in a sun-synchronous orbit that allows an almost constant vantage point of the sun. As a complement to the low resolution and small field of view of SUMER, TRACE has an 8.5 x 8.5 arcmin field of view and a higher resolution of about 0″.5 per pixel. The detector aboard TRACE is 1,024 pixels x 1,024 pixels complete with multiple filters at different passbands, letting TRACE observe emissions from the continuum to the extreme ultraviolet emissions of Fe IX, Fe XII, and Fe XV at temperatures from 4,000 K up to 4 MK. The observations used for this project were taken in 1,216 Å, or Lyman-α emission, and in 1,600 Å, a continuum emission that corresponds to a temperature of 4,000-10,000 K. Ultimately, the 1,600 Å emission was primarily used for data analysis as features appear much brighter, as opposed to the Lyman-α emission where the features closer to the solar limb were almost completely overwhelmed by the luminosity of the chromosphere. Another of TRACE’s strengths lies in its relatively quick cadence of about 40 seconds. As evidenced later in a series of images, this rapid succession of observations allows the observer to catch the evolution of some of the fastest of solar phenomena.

Although TRACE is an impressive observatory for solar studies and is noted for its steady high-resolution images, it ultimately has a lower resolution and a slower cadence than what is capable with the SST. But the obvious advantage of having a space-based observatory, as shown by this project, is the ability to obtain reliable information regardless of meteorological problems. The high quality of
data provided by the SST would have been a tremendous boon to this project, but thankfully the reliability of the space based observatories has provided impressive sets of usable data.
Chapter 2

Methods

As stated earlier, simultaneous observations from SUMER and TRACE were taken from May 24-27, 2004, of the northwest and southwest solar limb. Even though two data sets were available, the TRACE data had been studied more in depth by Williams College thesis and summer research students in recent years leading this project to focus on the unexplored SUMER data. Also, because SUMER focuses on such a small region of the solar limb, finding a feature in the TRACE data that was then found to correspond to a feature in the SUMER observations would be much less efficient. The approach was initially intended to search for spicules with the SUMER data by finding changes in the velocities that occur relatively simultaneously through different distances from the solar limb. Although the strongest signal was eventually discovered to originate from a coronal loop, the method of detection and analysis remained the same.
2. Methods

2.1 SUMER Data Reduction

Because the SUMER data was used to actually find the “spicule candidates,” data reduction and analysis for this project started with SUMER observations. Only after these candidates were identified was the TRACE data analyzed to determine the motions of the solar material visually. All SUMER data reduction was performed using programs written by Ingolf Dammasch (Royal Observatory of Belgium, Solar Influences Data Analysis Center) who visited Williams College during the summer of 2007 to teach the researchers how to use his programs and use the SUMER data to analyze solar phenomena. A suite of programs were used to take raw data from the SUMER Image Directory to the restore files needed for programs written in IDL (Interactive Data Language) with each subsequent program building on the corrections and utilizing the files generated by the previous programs.

All of the programs provided by Dammasch were edited from previously existing programs especially for use at Williams College, hence the “wc_” prefix. Running the program `sumer_header.data_functions.pro` beforehand enables the software to run in different computing environments, such as Wesleyan University or Williams College, as opposed to the MPAe (Max Planck Institute for Aeronomy, now known as the Max Planck Institute for Solar System Research) where they were originally written. This routine calls the specific functions that other institutions might not readily have access to.

The data for reduction was acquired from the SUMER catalogue website in the SUMER restore file format. For example, the first file received after unzipping the tarred file was titled `sum_r_20040524_08011419.07704_08`, with each segment
of the name containing significance to the data. In this particular example, the
title conveys a SUMER restore file taken on May 24, 2004, at 08:01:14.19 UTC
centered on the wavelength of Ne VIII (770.4 Å). The final “_08” corresponds to
the data format used throughout this project, with 50 spectral pixels, situated
around the target wavelengths of Si II, C IV, or Ne VIII and 360 spatial pixels,
centered approximately on the solar limb. In each study, there are 181 files for
each spectral window, totaling 543 files in all for each study.

After the data has been unzipped and the functions called with
*summer_header_data_functions.pro*, the next step of data reduction was to generate
an ASCII list of all observations during a certain scan in a specific wavelength.
The scan number is the internal key for that particular observation assigned by
SUMER, corresponding to the day the observation was taken with the final two
digits indicating what daily queue number the observation happened to occupy
for that day. For example, the above file was placed into the list
direct_s3097901_07704.lst, with the first number showing the scan number and the
second showing the central target wavelength. On the next page is a table of scan
numbers with their corresponding dates, start times, and fields of view on the
solar disk.
Each file was placed in the list with 180 other observations taken during the same scan centered on the appropriate spectral line, in this case Ne VIII (770.4 Å). All of the later programs use these lists as inputs to perform the same corrections on an entire wavelength scan resulting in a coherent and appropriately reduced data set.

The first program in the data reduction process is wc_headinfo.pro which requires the user to input the study, the substudy, which is also central wavelength in the spectral window, and the number of files in the ASCII list. The program then extracts header information from the list of SUMER restore files and prints data such as the first and last file, the number of files, and the exposure time, among many other values. The above example generated the file headinfo_s309701_07704.txt and studyinfo_s309701_07704.dat. The text file would be beneficial to keep record of for future reference, but the data file is necessary for use in later IDL programs.

The next program, wc_fast05.pro, displays different averages and overviews of each scan allowing the user to pick out cosmic ray detections and faults in the detector that can later be removed from the ASCII list. The “05” suffix corre-
sponds to the on-board compression method of the intensities that is commonly used in SUMER data. The program then displays an average intensity across the entire scan to select the significant upper and lower regions of the detector, so the entire 360 spectral pixels worth of information are never actually used. After determining the pixel significance, the program displays the average target spectral profile intended for the user to note the pixels that correspond to the intensity of the continuum and the target spectral line. On the next page in Figure 2.1, the continuum pixels, marked by squares, have been selected as pixel 5 to pixel 10 and pixel 48 and pixel 49 at the end of the spectral window. Additionally, the line pixels have been selected from pixel 21 to pixel 36. The positions of these continuum and line pixels would then be manually entered into the data file, or in this particular example, studyinfo_s309701_07704.dat, to be read and analyzed by programs later in the reduction process.

The next step in the reduction process involves running the program 

\textit{wc\_read05\_cube.pro} which takes the line and continuum pixel positions that were manually entered into the data file and corrects the observations for dead-time and gain, subtracts the continuum, and based on the line pixels and assuming for a Gaussian profile, estimates the line widths and shifts. This program also allows the user to operate a spatial pixel smoothing routine that smoothes the value of a pixel with 50\% of the values of the pixels on either side to enhance the signal-to-noise ratio. This routine was questioned after it was realized that the project would be pushing the SUMER data to the limits of its resolution and the information from one pixel would be skewed with the spatial smoothing. This dilemma is discussed later in the Problems section. The resulting data is
then saved in one restore file that contains all the information for the separate parameters (continuum intensity, line intensity, line shift, line width), for example, s309701_07704.rst. Finally, \textit{wc\_read05\_cube.pro} generates a .gif image such as the one seen in Figure 2.1, with the line and continuum pixels displayed on the spectral profile and a visual representation of the spectral window along the left side.

\textbf{Figure 2.1:} This image, generated by \textit{wc\_read05\_cube.pro}, shows the average spectral profile centered on Ne VIII. Selected line pixels are marked by asterisks while continuum pixels are marked by squares. Note that the peak of the line profile occurs at about 1,540.8 Å in first order, or at 770.4 Å in second order. The image represents a 50 pixel wide spectral window.

The program \textit{wc\_correct.pro} then takes the restore file generated by \textit{wc\_read05\_cube.pro} and in an interactive dialog mode, corrects each separate measurement for gaps in information, spatial orientation, and flatfielding. \textit{wc\_correct.pro} then generates a separate restore file for each parameter, four in all per wavelength,
and a fifth restore file to be used in the next program. For example, the created restore files would be, in accordance with the above pattern, s309701_07704_ with the suffixes of ba.rst for continuum radiance, li.rst for line intensity, my.rst for line shifts, si.rst for line widths, and dia.rst which contains measurements for all four parameter arrays and is used in the next few programs.

Then, \textit{wc\_displaypre.pro} is used to restore the dia.rst file and allows the user to change the display parameters, but is primarily used to restore the relevant restore file before \textit{wc\_display.pro} is run, which again uses a interactive dialog, but can be disabled if existing settings are desired. The program \textit{wc\_display.pro} creates scaled \texttt{.gif} images from the previous restore files through a series of different dialogs inherent with each measurement. For example, before generating the image for line intensity, the dialog displays an average intensity across the detector and asks the user to define the lower and upper limits of the radiance, along with the level of radiance significance, which designates values below as insignificant. The line shift dialog allows the user, among other possibilities, to subtract the average shift based on the detectors center of gravity or an alternatively calculated curvature of the detector, albeit north to south, or east to west. After each dialog specific to a different parameter is finished, the user has the decision to create the \texttt{.gif} image as seen on the next page in each of the four parameters which were generated from the ongoing example data.
2. Methods

Figure 2.2: The four .gif images generated by `wc_display.pro` from SUMER data taken in Ne VIII emission (770.4 Å) from the scan s309701. Note the horizontal detector fault visible at about the middle of the continuum and line intensity images. The plots are a time series with the spatial values as the y-coordinate and time as the x-coordinate.

The final program used in the data reduction process, `wc_info.pro`, takes the four restore files created with `wc_correct.pro` and generates a single new restore file with four 2D arrays, one for each parameter, and three 1D arrays files, two spatial arrays that contain either the x- or y-coordinate on the solar disk, and one that contains the time that each observation in the list was taken. The newly created restore file is like the previous files, but with the suffix “_info.rst.” For example, the final restore file for the above model would read s309701_07704_info.rst. These restore files are the final product of the reduction and are used in the original programs written specifically for this project that graph and help the user visualize the SUMER data.
2. Methods

2.2 Original Programs

For this project’s research with the SUMER data, four original programs were written to help analyze and extract the relevant information from the restore files created by Dammasch’s reduction process.

The first, `plot_time.pro`, produces graphs that show time-series plots of the radiance of a certain wavelength as it changes throughout the length of the entire scan. These radiance peaks allow the user to find energetic outbursts throughout the entire scan of a specific wavelength. While helpful, the strengths of SUMER lie in its ability to measure very accurate line-of-sight velocities and time-series plots of the radiance were foregone in favor of velocity graphs to use in the initial push to find spicule candidates.

Instead, effort was concentrated on the second program, `plot_shift.pro`, which initially operated very similarly to `plot_time.pro` as a way to identify spicule candidates by their velocities thereby utilizing the strengths of SUMER. In the final form of the program, `plot_shift.pro` takes input from the user on what particular study and wavelength to graph. Though a more complete discussion of the subject is offered later in the Problems section, a main requirement of the program was to find the solar limb before plotting velocities. Initially the y-coordinate of the peak continuum radiance was selected as the position of the solar limb, but because of the errors involved with the relatively low radiance, it was decided to find the y-positions of the somewhat brighter Si I peaks, one of which resides within each spectral window of the other emission lines, to find the limb. The Si I lines, while brighter than the continuum pixels selected from `wc_fast05.pro`, are still considered continuum lines. These brighter lines would then generate a stronger average
for the position of the limb than the previously chosen continuum pixels. After finding the y-coordinate of the limb, *plot_shift.pro* would plot the region generally understood to contain spicules, from 2,000–10,000 km above the limb, at five different neighboring heights. Each height was designated a different color that was displayed in a key above the graphs along with the position of the calculated limb. Also, because of a concern earlier about the spatial smoothing of the pixels, the program generated many different graphs, some depicting neighboring pixels while others skipped one or two pixels to determine if the trends could be a product of the smoothing or if the measurements were more substantial. The spicule candidates were then chosen based on the speed and coherence of the materials velocity through a wide range of y-coordinates.

For further purposes of visualizing the SUMER data, a third program was written titled *average.pro* that outputted the line intensities and line shifts centered on the time and y-coordinate of the observed surface phenomena in the three different wavelengths. Because the average radiances change based on their distance from the solar limb, the averages and standard deviations of each y-coordinate were generated as well to gain insight into the significance of the measurements. This information was read into data files that could then easily be imported into Microsoft Excel to generate 3D surface plots as a way to visualize the multidimensional data in one graph (Figure 3.7).

After the graphs from *plot_shift.pro* were analyzed and the loop feature was decided as the primary object of study, a final program was written solely to graph the twenty minutes of SUMER observations around the time of the feature. Because *plot_shift.pro* generates graphs that illustrate the entire duration of the
scan, a smaller graph was deemed necessary to zoom in on the feature to observe radiances and line shifts on smaller time scales. This program, titled \texttt{s309701.pro} because the strongest feature was found in study s309701, allows the user to select the wavelength, y-coordinate range, and what parameter to display, though only line shifts and radiances were used for this project.

\textbf{Figure 2.3:} Sample output from \texttt{plot\_shift.pro} of study s309701 in the Si II emission (1533.4 Å). Notice the peak between time 9.2 and 9.3, which corresponds to the coronal loop observed in TRACE data.
2.3 TRACE Reduction

As per the advice of Professor William Herbst of Wesleyan University and Professor Jay Pasachoff of Williams College, instead of cataloging every instance that seemed to indicate a spicule, the multitude of graphs resulting from *plot_shift.pro* were thoroughly searched for the strongest signals that would be able to render the most significant data. Three strong spicule candidates were identified and the dates, times, and durations of the events noted. Thirty minute stretches of images surrounding the time of the peak velocity of these strong spicule candidates were gathered from the TRACE image database and analyzed using the Java based image processing program, ImageJ. Before reduction, the TRACE image field of view was $384'' \times 384''$ while the SUMER field of view covers $1'' \times 300''$, although the region of interest actually covers approximately $20'' \times 20''$. This corresponds to a reduction in size more than 368 times smaller than the original image and pushes the limits of TRACE resolution without more sophisticated reduction techniques, which have yet to be performed. A more thorough explanation is discussed in the Problems section. Because the TRACE data was used primarily to identify the features that generated the SUMER velocity peaks, a thorough reduction process was not deemed necessary as with the SUMER data. ImageJ was used to facilitate this zooming in of the images, which were then used to create a movie that illustrated the evolution of the features. After carefully reviewing each of the three movies, the best visible example of the strong line shifts happened to be a coronal loop in the study s309701.
2.4 Problems

The original aim of the project was to use the strong shifts in the SUMER graphs generated by plot_shift.pro to find the positions of “spicule candidates.” These positions would then be used to identify the features in TRACE data. In reality, the movies composed of TRACE data did not reveal strong spicules, but instead identified a strong coronal loop, even though it was not the intention of the project. Actually, a program such as plot_shift.pro measuring the strongest shifts of a region over a certain period of time would probably find a loop rather than a strong spicule. Unless the spicule is inclined mostly towards the observer, the velocities measured would not be sufficient to generate a significant line-of-sight shift. Instead, a peak measurement of the line intensity, not the material velocity, in the
region populated by spicules, from 2,000 km to 10,000 km above the solar limb, would give the greatest probability of finding spicules. Still, SUMER revealed very interesting data about the coronal loop that will be discussed later in the Results section.

One of the greatest problems plaguing research near the solar limb is actually identifying the limb position. Because spicules require high resolution to be located, an accurate method was needed to find the limb with the highest possible precision. The program *plot_shift.pro* originally located the limb through a common method of finding the position of the average peak continuum radiance and designating that position as the limb. This idea was introduced by Dammasch during preliminary research conducted during the summer of 2007 at Williams College. But after initial trials of *plot_shift.pro* revealed systematic errors of the limb position for only the northwestern scans, a look back at the .gif images produced by *wc_display.pro* proved that the detector fault was more troublesome than previously believed. Because the fault is off-centered slightly toward the bottom of the detector, the northwestern scans had incorrectly added pixel values contributing to an artificial brightening about 13″ south of the solar limb. In the southwestern scans, the detector fault was far beyond the limb and would only pose a problem if emission lines that peaked further away from the limb, such as Ne VIII, were being studied in much more detail than this project required. Unfortunately, the detector fault first appeared on May 19, 2004, five days before this project’s observations were taken, although the fault was small at first and only caused somewhat of an inconvenience. But the fault gradually increased to include dozens of rows and today Detector A is no longer being used.
Instead, Detector B is now primarily used for spectroscopic observations. Though the SUMER detectors were originally designed for two years of use, at the time of this project the SoHO spacecraft is entering its 12th full year of service and is presently scheduled to operate through 2009. The problem has been identified as a failing Analog-to-Digital Converter (ADC) in the Time-to-Digital Converter box (TDC) and is thought to have occurred because of the lack of radiation hard, or radiation resistant, components of the device. Years of use coupled with exposure to the powerful solar wind have also begun to degrade a detector used by the Ultraviolet Coronagraph Spectrometer (UVCS), starting with the same few pixel rows and slowly growing to affect more of the observation (W. Curdt, personal communication, April 4, 2008).

Figure 2.5: This graph of the position vs. the average radiance across entire s309701 scan displays the detector fault that occurred as a result of the degradation of Detector A. Note the jagged radiance that occurs around the position 905 throughout the different wavelengths.
After the detector problem was remedied by placing boundaries on the possible position of the limb excluding the known position of the fault, slight random errors still occurred throughout many but not all of the studies. Intense outbursts during the scan would randomly offset the brightest points of the continuum giving values for the limb that would appear a few arcseconds off of the approximate position provided by Ingolf Dammasch. After acknowledging that the continuum might not be bright enough to reliably measure the position of the solar limb, Dammasch suggested a new, more effective method involving Si I lines very close in wavelength to our target emission lines and visible in the spectral windows. The relevant lines used were Si I (1,539.7 Å) near Ne VIII (measured in first order at 1,540.8 Å), Si I (1,547.3 Å) near C IV (1,548.2 Å), and Si I (1,532.5 Å) near Si II (1,533.4 Å). Though reduction of the target emission lines occurred early during summer research, re-reduction of the data was necessary to extract this Si I data from each spectral window. A perfect recreation of the original data reductions would have been extremely difficult, though for this project’s purposes, the brighter Si I lines have proved very useful in accurately determining the solar limb.

After correcting plot_shift.pro to account for detector faults, bright points, and a faint continuum, there were still slight systematic variations between the observed limb position from TRACE and what plot_shift.pro generated of about 3″. Upon closer inspection of the TRACE data and consultation with Dammasch, the SUMER data appeared to have a −15″ error in the pointing, putting the actual x-coordinates at about 265″ instead of the reported 250″. This changed the SUMER slit position from being slightly to the left of the observed loop to being slightly to the right of the loop. The equation to find the actual position of
the solar limb that was compared to the `plot_shift.pro` output is the equation for the radius of a circle, stated as:

\[ \sqrt{\text{Solar}_x^2 + \text{Solar}_y^2} = R_\odot \quad (2.1) \]

Because the y-coordinates of the SUMER observations are more robust and could spatially determine the position of the limb, the x-coordinates somewhat relied on the y-coordinates and were found to be off by a significant distance. The SUMER team, through more established methods, determined the y-coordinate of the limb to be about 918″, while the calculated distance of SoHO from the sun predicted a solar radius of about 956″. These values yielded 265″ as the approximate x-coordinate of the SUMER slit for this project’s observations.

\[ \sqrt{265''^2 + 918''^2} \approx 956'' \quad (2.2) \]

Another difficulty with the SUMER data was the approximately 19 minute raster at the beginning of each approximately 89 minute observation. The purpose of this project was designed around the strengths of SUMER, for example, the ability to observe a small portion of the solar limb for an extended period of time, but the raster made the tracking of spicule evolution quite complicated. During the raster, some strong velocity peaks were measured that might have yielded spicules in the TRACE data, but because of the small size of the target phenomena and the motion of the region observed with the SUMER slit, these candidates were eliminated. Also, the raster of each study is visible as a small dip in each image produced by `wc_display.pro`. Because this dip disrupts the average
radiance at a y-coordinate across an entire scan, the rastered observations have been excluded for the radiance averages and graphs as well. This means that more than 21% of each scan were raster images and therefore excluded from calculations.

Though this project used both SUMER and TRACE data, the main focus relied on the SUMER data that could be readily manipulated simply with an IDL computing environment, available at Wesleyan University, where the majority of this project took place. On the other hand, Williams College has enjoyed years of research work on TRACE data that requires a more sophisticated computing environment that the Williams Astronomy department maintains. Though previous student researchers at Williams College have written programs to accurately analyze radial motions as measured by TRACE, this past year, repeated efforts from Williams College students, faculty, and alumni have discovered an outdated and barely functional computing environment for past velocity determining programs like *followspicule.pro*, written by previous research students. While the two solar thesis students for 2008, Will Jacobson and Evan Tingle, have focused on SST and SUMER data respectively, less attention and upkeep has been paid to the TRACE computing environment at Williams College relative to recent years, leading both students’ projects to use the TRACE data in less detail and precision than the primary data sets.

Another concern, as mentioned above, involved the pixel smoothing process of the reduction routine which combined the value of a pixel with 50% of the immediate surrounding spatial pixels. The original purpose was to increase the signal-to-noise ratio, which normally would have been desirable, but because this project used the values of individual pixels and employed the limits of SUMER’s
resolution, the blended pixels seemed less advantageous. While constructing velocity graphs with *plot_shift.pro*, a feature was added to generate the plots with different intervals between the y-coordinates measured, to decrease or completely eliminate the effects of smearing at the expense of resolution. All of the initial strong spicule candidates survived this lowered resolution test, thereby signifying they were actual features and not artifacts introduced by the pixel smoothing routine.
Chapter 3

Results

For the purposes of this project, the line shifts, line-of-sight velocities measured using the Doppler effect, and the line radiances, the measurement of the target line emission sec$^{-1}$ arcsecond$^{-2}$, from SUMER were used. The observations of 1,600 Å emission and 1,216 Å emission from TRACE were used for detailed imaging and morphology comparisons.

3.1 Velocity Findings

After running the program on all four days of SUMER data, plot_shift.pro produced graphs showing atmospheric material that maintained seemingly random velocity dispersions. The solar material at the three target wavelengths would then occasionally increase or decrease simultaneously in velocity across multiple y-coordinates before returning back to the previous state of randomness, although in the Ne VIII emission evidence of these shifts was far less observable as the material behaved more erratically. These occasional simultaneous velocity shifts were
thought to be evidence for strong spicule velocities and were noted as “spicule candidates.” After focusing on three strong peaks and analyzing the corresponding TRACE data, two of the observed spicule candidates demonstrated strong shifts but were either too close to the limb or were not resolved as an identifiable solar feature. The observations from TRACE enabled the researchers to track the radial motions of the features while SUMER observed the line-of-sight motions. But the images also helped to actually identify the third spicule candidate as a small coronal loop. This loop was eventually chosen as the strongest candidate after many interesting velocity and radiance measurements were observed with SUMER, though the loop was not immediately recognized as the source of the shifts.

The observable beginning of the coronal loop has different connotations based on what wavelength and data set is being used. The beginning of the loop in the SUMER data appears to be where the material starts to decrease in velocity simultaneously at different y-coordinates in the C IV emission, which occurs approximately at 9:14:19 UTC. At the same time, the Si II material is being redshifted at multiple y-coordinates as well. The corresponding observations in the TRACE data show the bright footpoints where the coronal loop will connect with the solar surface, but the loop itself is not visible, suggesting a material flow without the magnetic loop being completely full of plasma. Later on the same graph of SUMER data, the material reaches the greatest velocity measured, be it redshifted or blueshifted, around 9:16:19 UTC. The peak velocities of the coronal loop reach −4.8 km/s in the C IV emission at y-coordinate 924.8′′ and 10.7 km/s in the Si II emission at y-coordinate 926.9′′. At the same time as the velocity
is peaking in the SUMER data, the TRACE observations reveal the first visible connection of the coronal loop, although it eventually becomes much brighter.

Though the visible loop in the TRACE data continues after the SUMER graphs lose the cohesiveness of the velocities observed earlier, as mentioned before in the Problems section, the pointing of the SUMER slit is not exactly on the loop but at a slightly larger x-coordinate. Because the slit observes a narrow 1" x 300" slit of the solar surface, detailed velocities of the entire loop are not available but instead only those slightly to the right of the loop are available. This seems to suggest, based on the approximate inclination of the loop visible in the TRACE data, that multiple loops are present though not completely illuminated by plasma flows. The velocities of the more extended and fainter loops appear to dissipate before the smaller brighter loop slowly dims, while the radiance graphs of the fainter loops suggest that the loop remains even as the coherent velocities decay.

One piece of evidence suggesting that the material velocities measured with SUMER are connected to the coronal loop observed with TRACE is the shape of the velocity graph. Figure 3.1, a velocity graph of Si II, shows the material at higher y-coordinates as it increases towards much higher velocities than the material closer towards the limb, although all of the velocities at the different y-coordinates increase, reach their peak, and decrease simultaneously. If the velocity shifts had been generated by material following a ballistic trajectory, the velocity graphs would have exhibited the higher velocities occurring closer towards the limb. But the greatest velocities are occurring higher in the solar atmosphere, while the lower velocities are occurring closer towards the limb. After speeding up to about 5 km/s, the Si II material closer to the limb maintains its velocity while
material at higher y-coordinate continues to speed up to a peak measurement of 10.7 km/s, demonstrating the acceleration of material as it travels higher into the solar atmosphere.

Another example of evidence of loop structure would be the y-coordinates where strong velocity shifts are measured. In the C IV data, the simultaneous shifts occur from 922.7″ to 927.9″ while in the Si II data, the shifts appear from 921.7″ to 931.0″. The areas covered in these two ranges suggest that material is passing into one part of the region observed by the SUMER slit and passing out through another. The width of the region excludes spicules traveling into the slit at an angle as they have been measured with widths of about 700 km by the SST and the cohesive velocities of the material rules out multiple spicules traveling into the slit at once.

Also, upon closer observation of Figure 3.1 and Figure 3.2 on the next two pages, the peak velocities, whether they are redshifted or blueshifted, occur at slightly different y-coordinates, which both occur at different latitudes than the visible TRACE data. Barring a significant pointing error, this would serve to illustrate multiple loops existing in very close proximity and different directional material flows at the different temperatures measured. The blueshifting of the hotter material concurrent with the redshifting of the cooler material might suggest that the hotter material, C IV, is originating at the furthest footpoint from the observer where the loop connects with the solar surface while the cooler material, Si II, is originating at the footpoint closest to the observer.
3. Results

Figure 3.1: Line shift graph of Si II emission (1,533.4 Å) generated by s309701.pro. Notice the strong redshifting of the Si II material at approximately 9:16 UTC.
Figure 3.2: Line shift graph of C IV emission (1,548.2 Å) generated by \textit{s309701.pro}. Notice the blueshifting of the C IV material at approximately 9:16 UTC.
Figure 3.3: This progression of TRACE images taken in the continuum wavelength of 1,600 Å with false color added shows the particular coronal loop first identified by SUMER.
3. Results

3.2 Radiance Findings

As witnessed in coronal loops many times larger than the one observed, the intense heating of the material can be seen at the apex of the loop. As the material is being pulled from the chromosphere, it is quickly heated to temperatures up to many millions of Kelvin, though the mechanisms for this heating are not yet quite understood. As shown on the next page, the loop observed was hot enough to be imaged in the Lyman-α emission, which corresponds to a temperature of 10,000 K–30,000 K, although this loop would be on the lower end of that range. Kano and Tsuneta (1991) have developed a scaling law using data from the Yohkoh solar satellite that states:

\[ T_{\text{max}} = 3.8 \times 10^4 (pL)^{1/5.1 \pm 0.5} \]  

where \( T_{\text{max}} \) is the maximum temperature of the coronal loop, \( p \) is the pressure measured in dyn cm\(^{-2}\), and \( L \) is the length of the loop measured in cm. This equation shows the relationship between the temperature, pressure, and length of a coronal loop and indicates that longer, high-pressure loops have greater temperatures than shorter, low-pressure loops. Because the observed loop occurred within the solar limb, estimates of its length are very difficult to come by, but clearly this small loop does not reach the intense temperatures of the bigger more spectacular coronal loops. A smaller loop with a weaker magnetic field would understandably generate cooler temperatures than those seen in larger types.
Another interesting observation was the change in radiance in the region above the coronal loop. Because the loop is pulling chromospheric material in a magnetic field line into higher regions of the solar atmosphere, one would expect to see an increase in the radiance of a cooler material that normally would not be found at that altitude. This increase in radiance of a cooler material is observed in the Si II line. But the C IV line, a hotter transition region line, is actually observed as decreasing in radiance. A probable explanation for this phenomenon might be that as the cooler Si II material is being pulled into the upper reaches of the solar atmosphere, it affects the hotter C IV material in a process known as masking. Masking occurs when a cooler material, such as Si II, passes in front of the hotter material, such as C IV, effectively absorbing its radiance. Because the intensity
of the emission lines, regardless of solar activity, decrease in luminosity as the observation moves away from the solar limb, the graphs on page 50 (Figure 3.7) have been reconfigured to portray the multiple of $\sigma$ of the radiance as a function of the average and standard deviation of the velocities at a specific y-coordinate.

Figure 3.5: Radiance plot for Si II emission (1,533.4 Å) from y-coordinates 929” to 933.1” generated by s309701.pro. Notice the increase centered on 9:15 UTC, especially at y-coordinate 930'.
Figure 3.6: Radiance plot for C IV emission (1,548.2 Å) from y-coordinates 929″ to 933.1″ generated by s309701.pro. Notice the decrease centered approximately on 9:17 UTC.
Figure 3.7: These two surface graphs illustrate the multiple of $\sigma$ differences between the average values of the radiance at a certain y-coordinate with the observed value. Si II radiance (1,533.4 Å) is represented in the top graph while C IV radiance (1,548.2 Å) is below.
As evidence of the masking effect, there is a significant decline in the C IV radiance around y-coordinate 929.0″, approximately from time 9:15:16 to 9:15:47 UTC, which corresponds to a low of $-2.26\sigma$. Oppositely, a significant increase is measured in the Si II radiance around y-coordinate 930.0″ at time 9:14:48 UTC corresponding to a peak of $3.21\sigma$. Although these are relatively small areas with short time periods for significant changes in the radiance, they are surrounded by larger regions that suggest the same story, though less significant.

The graphs also show that the changes in radiance are relatively concurrent; the greatest Si II radiance increase occurs about a minute sooner and one arcsecond higher than the greatest C IV decrease. This further suggests the existence of multiple coronal loops occupying a close proximity to one another, though not necessarily the same size or shape.
Chapter 4

Discussion

Based on the position and small size of the SUMER slit, this project’s observations were at the mercy of the sun and its magnetic forces. Observing features on the surface of the sun is never as predictable as most other forms of astronomy as the particular structure being observed can change on the order of minutes.

Although the program plot_shift.pro was originally written to find spicules, the strongest signals measured happened to originate from a small coronal loop. The inclination and position of the observed loop within the solar limb makes length measurements very difficult to come by, but this particular coronal loop measured in both TRACE and SUMER data is a relatively small cool loop, appearing extremely faintly in the 1,216 Å emission and only producing bright emission in the 1,600 Å continuum.

As observed in Figure 1.3, the northwest region, where the small coronal loop was found in the TRACE data, can been seen bordering a darker coronal-hole region. In this darker region, most of the magnetic lines are open field lines and
stream the solar wind into space. Coronal loops are more readily found in active regions, or the bright points on the solar disk, where intense magnetic activity takes place. The observed loop occurred in an area without these characteristic strong magnetic fields, which may explain why the loop found was so small. Although the loop observed in TRACE is orders of magnitude smaller than the more massive coronal loops observed in other projects, this loop still bears the trademarks, such as velocity shifts and material flows, visible in all loops.

4.1 Siphon vs. Symmetrical Flows

The greatest blueshifts for the region above the coronal loop observed in the TRACE data occurred in the hotter C IV at a peak velocity of \(-4.8\) km/s (Figure 3.2). Alternatively, the greatest redshifts measured occurred in the cooler Si II emission line at a peak velocity of \(10.7\) km/s (Figure 3.1). Though these measurements were not taken directly on the loop visible in TRACE, the relatively high velocities at high y-coordinates propose that a non-visible loop structure exists above the visible loop. Spadaro et al. have used observations from SUMER measuring the material line-of-sight velocity for typically sized coronal loops. Based on the velocity measurements taken by Spadaro et al., the velocities of this project’s SUMER observations could suggest the position of our slit relative to the loop. Their observations include SUMER spectral measurements with simultaneous images of the region’s magnetic field strength taken with the Michelson Doppler Imager (MDI) aboard SoHO. Spadaro et al. measures the material velocity of a loop that lies slightly outside the SUMER slit as approximately \(\pm 5\) km/s. This
corresponds to this project’s measurement of the hotter C IV coronal loop, which is blueshifted to \(-4.8\) km/s, placing this loop structure slightly outside the spectral slit. Oppositely, Spadaro et al. measured the velocities of coronal loops that were directly within the spectral slit as \(\pm(8–15)\) km/s. This suggests that this project’s measurements of the cooler redshifted Si II loop were more directly centered. This discrepancy in loop position is in accordance with previous observations that indicate coronal loops exist at different temperatures and “are not necessarily co-located within the same region, but may be significantly shifted from each other or have different shapes and sizes.”

For their particular project, Spadaro et al. were measuring the velocities of coronal loops exhibiting siphon flows, where one end of the coronal loop fills with material which follows the magnetic field line, and then deposits the material at the opposite footpoint. Though the resolution is low, the evolution of the loop in the TRACE data shows what seems to be a siphon flow, with a concentration of material originating at the far footpoint and traveling across the magnetic field line to the opposite footpoint. But instead of completely depositing the material there, the loop then retreats back to the original footpoint.

4.1.1 Changes in Radiance

While the paper by Spadaro et al. found these velocities corresponding to coronal loops with siphon flows, how can this project’s loops be understood while exhibiting both redshifting and blueshifting within the same region? The coronal loop symmetric-flow model, where material from both footpoints flows into the loop structure causing a concentration of material in the loop, might explain
the observations of blue- and redshifted material occupying the same region. Evidence of this can be seen in the radiance graphs, which show the cooler Si II material existing in the upper atmosphere for an extended amount of time, and consequently the decline of C IV radiance due to masking, after the velocities of the loop lose cohesiveness before dissipating. If the loop visible in the TRACE data is thought to be associated with the loop measurements made with SUMER, which this project supposes is the case, then either a siphon flow coronal loop could be observed with larger symmetrical loops above it, or the strange characteristics seen in Figure 3.3 might actually indicate a symmetrical flow. Logically, it seems that if the strongest visible loop exhibits siphon flow then all associated loops must exhibit siphon flows and vice versa, though this has not been proven observationally.

4.1.2 Line-of-Sight Velocities vs. Line Intensities

Spadaro et al. also says that there was a slight positive trend in their line-of-sight vs. line intensity suggesting that, “this is in agreement with the discussion...where we noted that the downflowing leg of the identified magnetic loop structures exhibiting siphon flows is usually brighter than the upflowing one.” This project’s observations were not able to include both the upflowing and downflowing legs of the loop, but instead possibly imaged both an upflowing and downflowing leg simultaneously. At the position of the SUMER slit, the downflowing leg, presumably the redshifed Si II loop, is indeed increasing in radiance and at one point reaches a peak of $3.21\sigma$. Unfortunately, despite the increase in line intensity, the average radiance of Si II in the region shown in Figure 3.7 is still much dimmer
than the C IV. Oppositely, the upflowing leg, presumably the blueshifted C IV loop, is decreasing in radiance but is still much brighter than the “downflowing” Si II loop. If the SUMER slit had scanned over a coronal loop that existed for more than this loop’s approximate lifetime of 5 minutes, true comparisons in each wavelength could have been accomplished.

Later observations of the material flows of coronal loops with Hinode’s Extreme Ultraviolet (EUV) Imaging Spectrometer (EIS) by Del Zanna show interesting results concerning the blue- and redshifts of atmospheric material. Corresponding to measurements introduced by Spadaro et al., Del Zanna measured line-of-sight redshifts in the observed loops from 5–10km/s. This paper shows that the blueshifted velocity measurements are stronger in hotter lines while the redshifted velocity measurements can more easily be found in the cooler lines. Although Del Zanna’s observations correspond to loops measured at much higher temperatures, the claim might still apply to loops with relative temperature differentials but just on cooler scales.

While the material velocities measured with SUMER are reaching their peaks, the radiances of the material are either simultaneously arriving at a maximum, as in the case of Si II, or simultaneously decreasing, as with C IV. To envision the increasing luminosity scenario of Si II, one can imagine the loop pulling the cooler chromospheric material into the higher reaches of the atmosphere, increasing the amount of material at that height where it is normally less prevalent. Oppositely, the C IV radiance is decreasing simultaneously as the Si II radiance increases. Because Si II is a chromospheric line and C IV is a transition region line, the radiances measured at the higher y-coordinates are opposite from what
they would normally be observed as. This decrease in radiance might occur as the Si II material is being drawn into the upper atmosphere, blocking the C IV emission in an effect called masking. The same effect is observed in observations of spicules at high energies, such as 171 Å. At this wavelength, the cooler spicules appear as absorption features in front of the hotter coronal material, giving them the nickname “dark jets.” Even though the evidence of such an event occurring is observable in the SUMER data, no such loop is visible in the corresponding TRACE images, though this does not necessarily mean that a loop is not present. Because the passband of the TRACE 1,600 Å ultraviolet continuum filter is 275 Å wide, it is possible that an increase in the Si II emission, whose Gaussian line profile is about 0.5 Å wide, would not make a noticeable difference in the image. Additionally, while the Si II emission was increasing, the C IV emission was decreasing, serving to somewhat balance the radiances.

4.2 Temperatures

This loop is quite cool compared to larger loops that are measured in the extreme ultraviolet. Some observations of active regions of the solar surface taken with TRACE using the 171 Å filter, which corresponds to a temperature up to 2 MK, show giant spectacular coronal loops that stretch high into the solar corona. Though this project’s TRACE data set included observations in 1,216 Å, or Lyman-α emission, most of the features were drowned out at this wavelength. The Lyman-α corresponds to a temperature of 10,000–30,000 K while the 1,600 Å continuum emission corresponded to a cooler temperature of 4,000–10,000 K. This
4. Discussion

continuum wavelength allows cooler features to be more easily observed, whereas in the hotter emissions, such as 1,216 Å, they are lost in the background of higher energy solar phenomena. This particular loop was very bright in 1,600 Å but was only faintly visible in 1,216 Å, indicating a relatively cool coronal loop.

4.3 Plage and Moss

During the length of the TRACE observations surrounding the time of the detection of the small coronal loop, two particular bright points can be seen in the middle of the image that eventually become the footpoints of the loop. These bright points, called plage, are associated with the strong magnetic fields generated within the sun. Often with larger, hotter loops in active regions, moss might be associated around the footpoints or in proximity to the coronal loop, but this is a much cooler, smaller loop. Though the plage areas appear arranged in similar patterns as moss, it is actually most evident in 171 Å observations and has been observed from 0.6–1.6 MK. Berger et al. (1999) claim that moss “is found only over magnetic plage areas that have associated 3–5 MK coronal loops.” Our loop can only be marginally detected at the hotter Lyman-α emission and is best visible in the 1,600 Å continuum emission. Therefore, the observed coronal loop and surrounding area is too cool to generate the moss phenomenon.

4.4 Multiple Loops vs. Multithread Model

Because the peak velocities and changes in luminosity observed in the Si II and C IV emissions in the SUMER data occur at different y-coordinates from each other
and from the TRACE data, it is possible that multiple loops or different strands of the same loop are being witnessed. The differential velocities measured within the features observed with SUMER coincide with the theoretical predictions presented by Warren, Winebarger, and Mariska that states that a multithread construction would help explain the extended light curves of the loops. The paper states, “the simulated light curves decay in about 150 s, while the observed light curves decay over about 900 s. A single cooling loop clearly cannot reproduce the extended decay of the observed light curve.” The size and lifetime of this project’s observed loop is much smaller than their particular measurement, but still outlasts the simulated light curve by approximately 150 seconds, giving evidence for the multithread coronal-loop model. Though differential material flows, one explanation for the blue- and redshifted observations, have not been identified, it is possible that these extended loops measured with SUMER have not been the subject of focus, as they are too dim to be observed with TRACE imaging. These dim loops could potentially contain multiple threads with different temperatures of material that travel at different velocities, though the possibility of multiple loops contributing to the velocity dispersions is supported more by current literature.

The diagram on the next page (Figure 4.1) illustrates the magnetic loop visible as a coronal loop in the TRACE data, and the magnetic loops whose velocities have been measured in SUMER data. Because magnetic loops exist at all positions on the sun, though primarily in active regions, it is possible to measure the velocity of material within the loop without it being filled with plasma, which makes the structure then a coronal loop and much more observable. Instead, the velocities measured correspond to a blueshifting of the C IV line between y-coordinates
922.7″–927.9″ and a redshifted of the Si II line between y-coordinates 920.6″–933.1″. This is presented below as the blueshifted line covers a smaller area than the redshifted Si II line, which can be seen at both higher and lower y-coordinates.

Figure 4.1: Illustration of multiple loops, or threads, existing in very close proximity. Notice the redshifted Si II line that is more directly measured by SUMER and contributes to the masking.
Chapter 5

Conclusions and Future Research

The observations of the solar limb by the SUMER instrument aboard SoHO yielded strong velocity shifts, which after viewing the corresponding simultaneous TRACE data, were attributed to the motions of a coronal loop. The shapes of the velocity and radiance graphs produced by s309701.pro after being run on the SUMER data reveal interesting evidence for a multithread model or multiple loops existing in very close proximity to one another, and cooler Si II material being pulled into the upper atmosphere and masking the hotter C IV material. Though SUMER’s spectral slit was not exactly on the coronal loop observed in the TRACE data, the shapes of the velocity and radiance graphs suggest that dimmer, more extended loops exist above the visible loop and are most likely attributed to the same magnetic field. The loops measured with SUMER are possibly connected to the visible loop’s bright footpoint regions as they probably exhibit the greatest magnetic field strength in the region.
5. Conclusions and Future Research

5.1 Future Research

Though all of the conclusions from this project can be drawn from the simultaneous observations, this corresponds to less than 10 minutes worth of data in a set of almost 11 hours simultaneously observed by TRACE and SUMER. Changing the program *plot_shift.pro* to find peaks in the continuum radiance, line radiance, or line width would require minimal effort and would open vast possibilities for new projects of study. Though follow up observations are impossible in solar observations, the data sets provided by SUMER and TRACE are incredibly rich and still have much to tell about the nature of the solar atmosphere.

5.1.1 SST

Even though SST images were originally taken simultaneously as the TRACE and SoHO observations, meteorological problems have prevented their incorporation into this project. As witnessed on the next page in Figure 5.1, the images from the Swedish 1-meter Solar Telescope can be of incredible quality and allow the observer to easily identify spicules and small magnetic loops. To enhance the resolution to approximately 0".1, the light path of the telescope has been turned into a vacuum and adaptive optics, which corrects for atmospheric seeing effects, has been installed. Because the adaptive optics require a strong feature to lock onto, such as a sunspot, observations of solar spicules that do not have distinct features do not implement the process. The observations from 2004 did not include the MOMFBD reduction technique, which was introduced in 2006 and implemented a 30 Hz cadence that is capable of producing over a terabyte of data daily. But
regardless of what reduction technique was used, the addition of high-quality
SST data would have been a significant addition to this project’s, and any other
project’s, study of the solar atmosphere.

![Sample image from SST after undergoing the MOMFBD reduction technique. Reduced by Michiel van Noort (RSAS/ISP).]

Figure 5.1: Sample image from SST after undergoing the MOMFBD reduction technique. Reduced by Michiel van Noort (RSAS/ISP).

5.1.2 STEREO (Solar Terrestrial Relations Observatory)

STEREO, a pair of solar observing spacecraft, has been designed to orbit in
front of and behind the orbit of the Earth, effectively giving a stereoscopic, or
3D, view of the solar surface. Because of the vantage point of solar satellites in
typical orbital positions, past observations of coronal mass ejections have yielded
information about only features that have not traveled towards the Earth. The
two observatories were launched October 26, 2006, separated, and after achieving
a heliocentric orbit started to drift further apart. Spacecraft A is situated slightly
inside and ahead of the Earth’s orbit, while Spacecraft B is slightly outside and behind the Earth’s orbit. Because of these differences, Spacecraft A is moving faster than Spacecraft B, effectively changing the angular separation between the two until an optimal position is reached. Equipped with coronagraphs, extreme ultraviolet imagers, radio burst detectors, and alternate vantage points, the main focus of STEREO is to study the stereoscopic properties and evolution of solar structures, most notably coronal mass ejections, from their origin to beyond the orbit of Earth. This will help solar scientists understand the nature of the event that is on a course towards Earth and will take space weather forecasts a great leap forward.

5.1.3 Hinode

While SoHO and TRACE have proven to be invaluable in studies of solar activities, their capabilities have been eclipsed by more modern observatories. One of the most exciting new solar observatories, Hinode, a Japanese Aerospace Exploration Agency (JAXA) solar satellite with collaboration from NASA and the United Kingdom’s Royal Astronomical Society, was launched on September 22, 2006. Recent observations with the telescope’s X-Ray Telescope (XRT) has revealed coronal structure on a complex scale that has not been seen before. In one specific example of the efficacy of the solar satellite, Hinode has recently been credited with the discovery of the origin of the solar wind after observing charged particles escaping the solar atmosphere when two regions connected by a large coronal loop merged.

Among other solar observatories, the combination of SoHO and TRACE ob-
servations still prove incredibly useful. In the discovery of the source of the solar wind by Hinode, SoHo’s Michelson Doppler Imager (MDI) measured the magnetic fields of the regions connected by the large coronal loop. TRACE and Hinode’s XRT frequently observe the same region to gain multiple wavelength observations to more fully understand the phenomena. Because the feature will be visible for only a limited amount of time, confirmation is also helpful when determining the nature of a structure or feature.

The combinations of different solar observatories allow the strengths of each to contribute to a greater understanding of the solar feature and the sun as a whole. Just as multiple wavelength observations of galaxies reveal different qualities inherent in those passbands, so too do solar features need different observations to add more pieces of the puzzle than one observation alone. But solar phenomena occur on the order of minutes or days, which require actual simultaneous observations with multiple solar telescopes. TRACE and SoHO, while somewhat outdated compared to the newest solar observatories, have made incredible observations of their own, will continue to assist the observations by the more modern observatories, and will remain significant contributors to solar science in the coming years.
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